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US Army Corps of Engineers
Water Resources Support Center
Institute for Water Resources

GUIDELINES FOR RISK AND UNCERTAINTY ANALYSIS IN WATER RESOURCES PLANNING

Volume I

- Principles -

With Technical Appendice

MARCH 1992

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Guidelines for Risk and Uncertainty Analysis in Water Resources Planning

Volume I

- Principles -

With Technical Appendices

Prepared for
U.S. Army Corps of Engineers
Water Resources Support Center
Institute for Water Resources
Fort Belvoir, VA 22060-5586

Prepared by
The Greeley-Polhemus Group, Inc.
105 South High Street
West Chester, PA 19382

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PREFACE

This report is a product of the U.S. Army Corps of Engineers Risk Analysis Research Program managed by the Institute for Water Resources which is part of the Water Resources Support Center. The report was prepared to fulfill part of several work units in the research program. These work units focused on developing and applying risk analysis methods and techniques to the main Corps areas of flood control and navigation. This report also fulfills part of additional work units on risk preference and risk communication.

The report describes in detail the process of using risk analysis in project planning and evaluation. In doing so, it conforms to the basic planning model and risk and uncertainty analysis recommendations presented in "Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies" (P&G). Although this report specifically addresses planning issues, the concepts and approaches to problem solving are applicable to engineering and operations as well. In addition, although the focus of the example applications is flood control and navigation, the risk analysis process and the techniques described are equally applicable to all other Corps project outputs.

The risk analysis framework involves the well recognized four basic steps in dealing with any risk: characterization, quantification, evaluation, and management. The purpose of conducting these analyses is to provide additional information to Federal and non-Federal partner decision makers on the engineering and economic performance of alternative investments that address water resources problems. The aim is to produce better decisions and to foster the development of the notion of informed consent by all parties to an investment decision.

Volume I, "Principles," provides an overview of the terminology and concepts of risk analysis as applied to water resources. It introduces the planner to a thought process and approach to solving water resources planning problems that explicitly recognizes risk and uncertainty. Volume II, "Examples," illustrates the application of many of the principles, concepts and techniques introduced in Volume I as applied to two idealized, but realistic case examples. These examples more fully develop the concepts as applied to the risk problems common in water resources investment planning.

This report was prepared by The Greeley-Polhemus Group, Inc. under terms of a contract with the U.S. Army Corps of Engineers Institute for Water Resources. Dr. Eugene Z. Stakhiv was the initial contract manager and was succeeded by Dr. David A. Moser of the Technical Analysis and Research Division. Dr. Moser, assisted by Mr. David J. Hill served as final editors. The Chief of the Technical Analysis and Research Division is Mr. Michael R. Krouse and the Director of IWR is Mr. Kyle Schilling. Mr. Robert Daniel, Chief, Economics and Social Analysis Branch, Planning Division, and Mr. Earl Eiker, Chief, Hydrology and Hydraulics Branch, Engineering Division, HQUSACE, served as technical monitors for the research program. Numerous field reviewers provided valuable insights and suggestions to improve early drafts.

GUIDELINES AND PROCEDURES FOR RISK AND UNCERTAINTY ANALYSIS IN CORPS' CIVIL WORKS PLANNING

Volume I: Principles

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CHAPTER 1

INTRODUCTION

INTRODUCTION

Water resource planners have long recognized the risks and uncertainty inherent in the work they do. The fundamental purpose of their endeavors is to formulate solutions that cope with a range of natural hazards that affect the safety of individuals and the economic productivity of communities. The degree of flood protection, the reliability of water supply, the safety of navigation are all explicit planning objectives that deal with risk reduction. When we devise operating rules for reservoirs we are inherently dealing with situations of risk and considerable uncertainty as to the performance of our designed systems. Working with complex natural, social, and economic systems, planners formulate and evaluate alternative plans to solve problems and realize opportunities. Knowledge about these complex systems and the complicated interrelationships between them is less than perfect. Information used to describe those systems in forms planners can analyze is often incomplete. As a result, the products of the planning process, the forecasts of with and without project futures, the project's performance and impacts, and the benefits and costs are never certain.

Since the Corps program explicitly deals with risk and uncertainty, the purpose of this guide is to construct an approach that formally explicates these fundamental issues in a uniform manner. Risk and uncertainty analysis is about improving information and ultimately, the decisions based upon that information. This is reflected in the Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies (P&G) of March 10, 1983, which states:

> "The planner's primary role in dealing with risk and uncertainty is to identify the areas of sensitivity and describe them clearly so that decisions can be made with knowledge of the degree of reliability of available information."

Although planners have implicitly recognized risk and uncertainty in their work, an explicit treatment of risk and uncertainty in planning documents has been lacking. And while the P&G mandates risk and uncertainty analysis, it fails to provide sufficient guidance on conducting one.

It is worth noting that the Corps already uses quite acceptable forms of risk and uncertainty analysis. The best known example is found in the estimation of expected annual damages for flood control studies. Corps planners routinely use probabilistic risk-based types of analysis in water supply studies, dam safety analysis, and in the many analyses that use frequency curves.

PURPOSE OF THE GUIDELINES AND PROCEDURES

The intention of these guidelines and procedures is to serve as a guide for conducting and incorporating risk and uncertainty analyses in the water resources planning process. The purpose of which, is to provide the basis for a useable procedure that will generate a more explicit treatment of risk and uncertainty within the Corp's planning framework. This will result in an improved understanding of the quantity and quality of the information we have and the quantity of information we do not have, for the sole purpose of improving decision making.

This report is directive rather than prescriptive in intent. No report of this nature can address all concerns, or prescribe an approach for all situations. The guidelines and procedures presented in this document are no exception. Instruction is its purpose, and it does provide some instructive detail on accepted mathematical and probabilistic techniques for identifying key factors to which benefit-cost analysis may be sensitive. The report introduces well-developed procedures, basic principles, and their interaction in the pursuit of risk and uncertainty analysis.

These guidelines and procedures are intended to illustrate the background and principles involved in risk and uncertainty analysis in order to provide direction in conducting an analysis. The report is intended to be used as a reference guide, emphasizing an integrated framework for risk and uncertainty analysis within the Corps' planning process. It is not a comprehensive listing of issues, problems, or techniques related to risk and uncertainty analysis. Based on the conceptual framework of the P&G, the report elaborates on, provides examples, and explanatory materials for how this can be carried out in a manner that builds on current Corps planning and analysis practices.

Volume I of this report is the instructional set of procedures and guidelines for conducting a risk and uncertainty analysis. Volume II contains two case studies, one of a hypothetical urban flood control project, and another of a hypothetical deep draft navigation project. The case studies illustrate the application of many of the concepts, principles, and techniques for risk and uncertainty analysis described in Volume I.

Finally, this report seeks to further the goal of increasing acceptance of risk and uncertainty analysis as a valued and integral part of the Corps' planning process. It is hoped that these guidelines and procedures will:

1) alleviate concerns that Corps personnel have regarding potential difficulties inherent in risk and uncertainty analysis;
2) compliment existing engineering and planning regulations that promote various aspects of risk and uncertainty analysis in all phases of planning and design;
3) prepare more user-friendly risk and uncertainty analysis for Corps analysts and decision makers alike.

INTENDED AUDIENCE

These guidelines and procedures are primarily designed for Corps of Engineers planners, analysts, decision makers, their counterparts among non-Federal project partners, and others working within the Corps' planning context. The contents of this report have been developed with this specialized audience in mind. For that reason, selected definitions, nuances, and contexts presented here may not be appropriate for other risk and uncertainty analyses conducted in other contexts. Until an accord on the universality of concepts and definitions is reached in this rapidly developing multi-disciplinary field of endeavor, semantic conflicts among contexts are unavoidable.

ORGANIZATION OF THE GUIDELINES AND PROCEDURES

Volume I of this report, the implied guidelines and procedures, consists of seven chapters, a bibliography, and ten appendices. The seven chapters develop the nature of risk and uncertainty analysis in the context of the Corps planning process and projects. Appendices contain technical details and are provided as overviews of methods used for risk and uncertainty analysis. The bibliography provides a list of some excellent references for further guidance on this topic.

Chapter 2 undertakes the substantial task of defining the subject matter. Despite advances in both the art and the science of risk and uncertainty analysis, substantial confusion exists among practitioners over how risk and uncertainty analysis is to be used in the context of their everyday tasks, programs, and missions.

Following the definition of basic concepts and terminology in Chapter 2, Chapter 3 applies these concepts in a general fashion to the Corps' planning process. In Chapter 4, potential sources of risk and uncertainty in specific types of Corps projects are discussed.

Techniques for dealing with risk and uncertainty analysis are discussed in a general fashion in Chapter 5. Appendices provide additional details on some of these techniques.

Chapter 6 is devoted to the communication and display of risk and uncertainty issues. Chapter 7 outlines a "work plan" that suggests an approach and provides guidance for integrating risk and uncertainty analysis into the framework of the Corps' planning process.

Lastly, the appendices provide brief descriptions and example applications of selected tools used in risk and uncertainty analysis.

CHAPTER 2

BASIC CONCEPTS

INTRODUCTION

Defining what is meant by risk and uncertainty analysis is a necessary first step. It is also a difficult step because different people in various professional disciplines interpret what is meant by risk and uncertainty analysis differently. As used in the context of the Corps' planning process, risk and uncertainty analysis is a unique amalgam of several well-developed fields of inquiry. It is part decision science, part planning theory, part theory of statistics and probability, and part benefit-cost theory. Every associated field of inquiry employed in water resources planning, e.g. ecology, economics, social science, and engineering possesses its own professionally developed viewpoint and procedures for risk analysis.

This chapter provides Corps planners and decision makers with an understanding of what risk and uncertainty analysis means within the framework of the Corps' planning process. It does not attempt to establish a standard set of definitions for the entire universe of risk and uncertainty practices, but will develop the concepts within the context of the Corps needs. First, an overview is provided of the inherently risky and uncertain nature of the Corps' planning environment and why risk and uncertainty analysis is important for better planning. Then, definitions of risk, uncertainty, and risk and uncertainty analysis, tailored to fit the planning process, are developed.

OVERVIEW OF RISK AND UNCERTAINTY IN CORPS' PLANNING

The Corps' planning process is a classic decision making model based on the scientific method developed hundreds of years ago. In this planning dimension uncertainty means simply the lack of certainty. It is the reality of inadequate information. When information is imprecise or absent, that is uncertainty.

Uncertainty, arising from inadequate information, is a major problem in the Corps' planning process. The traditional solution to this problem is to increase design safety factors or to increase the quantity and quality of information. The latter solution is performed through techniques such as expanding the data base, eliminating or minimizing measurement errors, and using traditional statistical analyses. Nonetheless, the range and diversity of problems encountered by Corps planners is pushing them beyond currently accepted planning practices of dealing with uncertainty into the emerging field of risk analysis.

Uncertainty is inherent in any future-oriented planning effort. Planners rarely have all the information needed to make the kind of public investment decisions that are expected of them. They often do not know how much confidence to place in the information they have and must make decisions in an uncertain political, social, and economic environment. In addition, many of the problems they are trying to solve are characterized by the hazards that arise from so many random natural processes and systems. To complicate matters further there is uncertainty about these hazards.

To add to the complexity, a varied group of parties are interested in the planning process and contribute their diverse and often disparate understandings of the risk and uncertainty analysis. Analysts face substantial problems of identifying, analyzing, and mitigating the various sources of risk and uncertainty. Decision makers must weigh the trade-offs presented by the analysts and decide or resolve issues of dispute among them. The public must live with the decisions made on the basis of these analyses. Each group of analysts has its unique perspective on what is risky and uncertain, and professional differences exist in applying and interpreting the results of the various analytical approaches.

Water resources planning has always required at least an implicit handling of risk and uncertainty issues. The stochastic nature of natural processes and the occurrence of natural hazards is obvious. These circumstances lead to classical risk situations.[1] Superimposed on these stochastic processes is uncertain and unpredictable human behavior.

The P&G emphasize the need for planners to recognize that there is significant uncertainty in the data and assumptions used in the formulation and evaluation of planning alternatives. Data may be incomplete, unavailable, or prohibitively expensive to collect and assimilate. The complex interrelationships among economic, engineering, environmental, natural, social, and political systems inherent in water resources planning requires considerable simplification by the use of assumptions. Everything cannot be studied because there is neither time nor money to do so. Decisions and choices must be made based on incomplete information. Planning attempts to aid informed judgment. Risk analysis contributes to this judgment.

The P&G describes a clear role for the planner whose primary role in dealing with this inherent lack of certainty is:

> "... to identify the areas of sensitivity and describe them clearly so that decisions can be made with knowledge of the degree of reliability of available information."

Perhaps rather subtlely, the P&G also creates a distinct but related role for the decision maker. The planner identifies and describes the risk and uncertainty so that decision makers can use this information in making decisions. The P&G are thus consistent with the widely recognized model that, at least conceptually, separates risk and uncertainty analysis into two distinct components, as shown in Figure 2-1.

The most important outcome of risk and uncertainty analysis in the Corps planning process is improved decision making. To achieve this involves assessing and managing the risk and uncertainty in data and assumptions, and also in the alternative plans and projects formulated using these data and assumptions. A necessary first step is to define some terms and concepts, the task of the remainder of this chapter.

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[1] Intuitively, a classical risk situation can be illustrated by floodplain occupancy. There is no question whether a flood will occur or not. The only issues in doubt are when will the flood occur, i.e., what is the probability of a flood in any given year, and what damages (consequences) will result from the flood when it does occur.

In classical risk situations the probability and consequences of, say, natural hazards can be estimated by reasonable means. Estimates of expected annual flood damages provide an excellent example of a classical risk assessment.

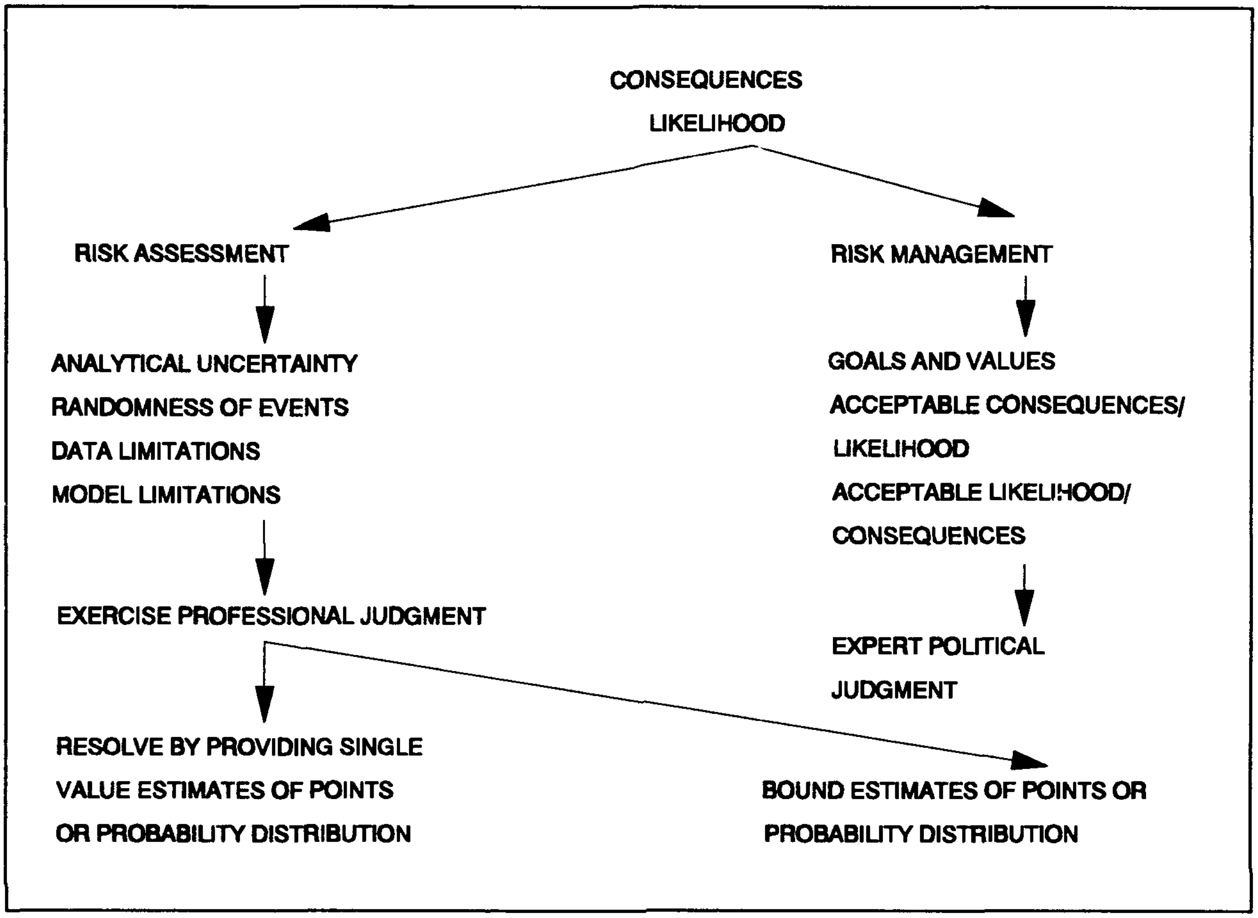

Figure 2-1: Risk Analysis

BASIC CONCEPTS AND DEFINITIONS

Frank Knight's pioneering book, Risk, Uncertainty and Profit, originally published in 1921 identified three basic situations facing decision makers:

1) complete certainty,
2) risk, and
3) uncertainty.

His definitions remain as standards for the literature.

Complete certainty is defined as a situation where the decision maker knows each possible alternative available and its exact outcome or "state of nature."

Risk is defined as a situation where the decision maker knows all the alternatives available but each alternative has a number of possible outcomes. Thus, the decision maker no longer knows the outcome of each alternative. In this region, probabilities are assigned to each outcome.

Two types of risk can be distinguished based on the probabilities used. Objective risk means the probabilities are objectively estimated. One way is *a priori* (in advance of the fact) through deductive reasoning, such as the probability of a head on a flip of a coin. In the planning arena, there are very few instances where *a priori* probabilities exist. Most objective probabilities are *a posteriori* (after the fact). One of the best examples is frequency analysis of historic streamflow data. Probabilities based on *a posteriori* methods are reliable only when based on a large number of observations. Subjective risk relies on people's beliefs about the likelihood of events. Subjective probabilities (expert judgement) are fairly commonplace in the world of planners because they often have some familiarity with a situation but not enough to be able to compute objective probabilities.

Uncertainty is defined by Knight to mean that probabilities cannot be assigned to the outcomes. A decision maker may know all the possible outcomes but have no way of assigning probabilities; or only some of the alternatives or their outcomes may be known. In the extreme, decision makers may be faced with complete ignorance.

Despite Knight's pioneering work, risk and uncertainty have taken on nuances in meaning that render his definitions less than adequate for all situations. No standard definitions have evolved, and the same concepts are encountered under different names in different contexts. This has disoriented many people trying to understand risk and uncertainty analysis. While confusion over the precise meaning of terms may persist among various disciplines for some time, the definitions that follow will standardize the language for the Corps. If and when a standardized set of terms is developed these definitions states here should be reconsidered in that light.[2]

Uncertainty in a General Sense

Planning is primarily concerned with searching for information about feasible courses of action. If we have all the information required to make a decision we have decision making under certainty. But choices among alternatives still have to be made even with perfect knowledge. Under these circumstances incorrect choices may be made even though the outcomes are known with certainty.

In the most general sense, uncertainty is the absence of certainty. Because we rarely have all the information we need or want, and most information deals with future unknown circumstances, most decisions are made under conditions of uncertainty. Consequently, the Corps' planning process is a classical example of decision making under uncertainty whether it be for planning harbor improvements, water supply, or flood control.

In this broadest sense, uncertainty is an all-encompassing concept ranging from minor imprecisions in the data base to a complete lack of knowledge or even conviction about an outcome or result. Uncertainty denotes a situation characterized by less than perfect predictability of events and/or outcomes.

[2] The Society for Risk Analysis is working on a glossary of terms for risk analysis. Lawrence B. Gratt's 1987 article "Risk Analysis or Risk Assessment: A Proposal for Consistent Definitions" reports on this effort and provides the basis for the definition of some basic terms in this manual.

Uncertainty, in this broad sense, can be and has been characterized in any number of ways. The first basic distinction is between the unknown and the unknowable. With objective uncertainty an individual possessing all the available information would still be unable to predict an outcome accurately. In this case the outcome is *unknowable.* Subjective uncertainty describes a situation in which the individual is unable or believes he is unable to predict an outcome with any degree of reasonable accuracy given the information he has or the cost of acquiring more information. In this case the outcome is unknown.

Uncertainty is the indeterminancy, through absence of plausible information or otherwise, of some of the elements that characterize a situation. To consider the nature of the unknown or unknowable we can review Rescher's (1983) three basic modes of uncertainty:

1. Probability uncertainty arises when some of the relevant probabilities are undetermined or underdetermined.
2. Outcome uncertainty arises when some of the relevant outcomes are undetermined or underdetermined.
3. Result uncertainty arises when some of the relevant results of the above outcomes are undetermined or underdetermined.

Probability uncertainty means we don't know the likelihood that something will or will not happen.[3] Though probability affords us one way of addressing uncertainty about outcomes the probabilities themselves are matters about which we may be uncertain. It does not matter whether there are no known objectively determined probabilities or simply that we are unable to say what the relevant probabilities are. Either way we are unable to specify some of the essential probabilities of the situation.

An example of undetermined probabilities may be given by the consequences of a dam failure. We do not know the probability that 1, 1,000, or 10,000 lives will be lost in the event of the catastrophic failure of a dam upstream of a town with a population of 50,000 at risk. An example of an underdetermined probability is where we know the passing of two vessels within a channel will result in one of three things: a safe pass, a grounding, or a collision. We may know that a safe pass occurs with a probability of 0.999. But, because the probability of a collision, p_c, is unknown we can only say that the probability of a grounding is $0.001\text{-}p_c$.

Probabilities are estimated by analysts on the basis of often inconclusive data. Accordingly they are not quantities whose exact values we can be dogmatic about. Some element of probability uncertainty will usually be present.

Outcome uncertainty is, perhaps, the most serious type of uncertainty. At one extreme of outcome uncertainty we are at a complete loss to say what will happen, either about the pathways of failure or the outcomes. For example, what would be the ecological, social, and economic outcome of a collision between a Liquefied Natural Gas (LNG) vessel and a super-tanker loaded with oil? Although a reasonably credible series of studies based on hypothetical scenarios can be accomplished to bound the problem, perhaps the most honest answer is we simply don't know, with any reasonable level of accuracy.

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[3] Denoting by p the set of probabilities p_1, p_2,...of a set of alternative events e_1, e_2,... this is a situation where: (a) p is not known or (b) data permitting the estimation of p are not known.

Not all outcome uncertainty is of this extreme variety. Some may result from an underdetermined knowledge of outcomes. For example, what would be the outcome of another severe flood in the near future on a recently flooded, aging commercial district? There may be strong emotional and economic ties to the current location and a lack of alternative sites that lead one to believe these people will occupy the flood plain indefinitely. On the other hand, the businesses may not have the financial resources to recover from another flood. This could lead to evacuation of the flood plain by some or all of the firms, leaving the land and buildings abandoned. We do not know what will happen.

Outcomes are underdetermined when we do not consider a range of outcomes that includes all possibilities. We may identify two outcomes as we have above, but what if a third occurs?

Result uncertainty means that given an outcome we do not know its result or value. A flood with an annual probability of 0.01 occurs and reaches a flood stage of +15 in town. What are the damages (i.e., what is the result)? What is the loss? The answer depends on so many variables that the result is indeterminate. What time of year, month, day does the flood occur? Was there any warning? How much? How long did the flood last? Was there ice, debris, sediment, oil in the water? Many times we may know what happens, its probability of occurring, and yet we still don't know the result.

These three categories of uncertainty are not mutually exclusive. Any situation may be uncertain in one or more mode.

Risk in a General Sense

In its broadest sense, risk is a subset of uncertainty: all risk situations are uncertain. But there are elements of risk that usually are used to distinguish it from the larger set of uncertainty.

Webster's Third New International Dictionary (1986) defines risk in part as follows:

> "(1) the possibility of loss, injury, disadvantage; or destruction: contingency, danger, peril, threat (2) the chance of loss or peril to the subject matter of insurance covered by a contract; the degree of probability of such loss (3) the product of the amount that may be lost and the probability of losing it."

The Risk and Insurance Management Society (RIMS) in 1985 defined risk as follows:

> "(1) Possibility of loss or exposure to loss. (2) Probability or chance of loss. (3) Peril which may cause loss. (4) Hazard or condition which increases the likely frequency or severity of loss. (5) Property or person exposed to loss. (6) Potential dollar amount of loss. (7) Variations in actual losses. (8) Probability that actual losses will vary from expected losses. (9) Psychological uncertainty concerning loss."

These definitions convey two distinguishing elements of the risk concept. The first suggests a probabilistic nature, variously expressed in terms of possibility, chance, or probability. The second suggests an adverse consequence. The risk literature contains a great variety of alternate definitions, but in virtually all of them risk implies a possible but not deterministic outcome.[4] In some contexts, risk has been used more or less as a synonym for probability, ignoring the adverse consequence dimension.

The U. S. Nuclear Regulatory Commission's 1975 report, WASH-1400, (the Rasmussen report) one of the best known in the risk field, expressed a technical definition of risk as follows:

(2.1) Risk = Frequency · Magnitude
(2.2) Frequency ≡ events / unit time
(2.3) Magnitude ≡ consequence / event
(2.4) Risk ≡ consequence / unit time

This definition is consistent with this guide's earlier characterization of uncertainty in the broad sense. Frequency is equivalent conceptually to probability uncertainty, events to outcomes, and consequences to results. What makes a situation risky rather than uncertain is the availability of objective estimates of the probability distribution. Mathematically, risk can be represented by a random variable described by a probability distribution. Let X be a random variable taking the value x, representing the events that describe the adverse consequence or risk. Let P(x) be the probability density function that represents the risk. Furthermore, let risk be a function of time so we have X(t) and P(x(t)). Expected risk is now precisely defined as:

$$(2.5) \quad \int_{0}^{\infty}\int_{-\infty}^{\infty} x(t)P(x(t))dxdt$$

The point of this line of reasoning is that the probability and the adverse consequence (outcome and result in the prior terminology) are clearly not completely separable variables when defining risk. Mathematical definitions offer an elegance that escapes most definitions of risk in common usage. The definition of risk used in this report and applicable to Corps analyses combines the scientific or mathematical form of the term with a common, understandable form.[5]

<u>Risk and Uncertainty in the Corps Planning Process</u>

Risk and uncertainty remain to be defined in an operational way for use in Corps analyses, so let's summarize some basic points. First, any situation that is not certain is by definition uncertain. Second, the lack of certainty stems from insufficient information; the information may be unknown (i.e., unavailable) or unknowable. Third, the nature of the uncertainty can be categorized by the type of information that is missing, but the resulting categories are not necessarily mutually exclusive. Risk is a special case of uncertainty in its general context.

Risk and uncertainty are often differentiated on the basis of what has been described as probability uncertainty. The P&G describes risk situations as "...those in which the potential outcomes can be described in reasonably well-known probability distributions." Situations of

[4] Gratt's (1987) article provides an excellent summary of several definitions of risk used in the literature.

[5] This definition, presented in the following section, has been proposed by Gratt (1987).

uncertainty are defined as those in which "...potential outcomes cannot be described in objectively known probability distributions." This latter definition does not preclude use of subjective probabilities.

Building upon these basic definitions by incorporating some points of our earlier discussion, the operational definition of risk for Corps' planning is as follows:

Risk: The potential for realization of unwanted, adverse consequences; estimation of risk is usually based on the expected result of the conditional probability of the occurrence of event multiplied by the consequence of the event, given that it has occurred.

This definition remains consistent with the definition of risk contained in the P&G while going a little further by suggesting that risk should encompass the notion of adverse consequences. The common idea of potential adverse consequences is incorporated, as is the mathematical concept of expected values.[6]

The operational definition of uncertainty for use in Corps' planning is adapted from the P&G as follows:

Uncertainty: Uncertain situations are those in which the probability of potential outcomes and their results cannot be described by objectively known probability distributions, or the outcomes themselves, or the results of those outcomes are indeterminate.

The essence of this working definition is to create a distinction between uncertainty in the broadly defined sense of a lack of certainty and uncertainty in the present narrow sense that excludes those situations that can be considered risky.

The above arguments can be restated as follows:

(2.6) $U = r \cup u$
(2.7) $r \cap u = \emptyset$
(2.8) $r \subset U$
(2.9) $u = r'$

Where U is the set of all situations that are not certain, i.e., U is uncertainty broadly defined; r is a set of all situations of risk; u is the set of all non-risk uncertain situations; ø is the null set; and, r' is the complement of r.

[6] Expected risk is by no means the only measure of risk. Expected annual flood damage is an expected risk value that is familiar to most Corps analysts. Other possible measures of risk include expected risk over a specific time period T, expected utility theory, prospect theory and risk aversion measures to name a few.

A Caveat for the Corps Planner

Now that some distinction between risk and uncertainty has been made, a caveat for the planner may be in order: do not become inextricably trapped in trying to identify what is risk and what is uncertainty! It is not as important to accurately label a situation as risk or uncertainty as it is to investigate how the lack of complete certainty may affect project formulation, evaluation, selection, and implementation.

In this respect it is helpful to look at risk and uncertainty as locations along a continuum of knowledge. Figure 2-2 shows this continuum with its extremes of complete certainty and complete ignorance. The Corps rarely operates at either extreme, so our primary interest is in the region surrounding risk and uncertainty.

The right end of this region is comprised of objective risks. Proceeding to the left, probabilities become less statistically sound and gradually merge into subjective probabilities. At some point in the continuum, uncertainty takes over and no probabilities can be assigned. By their very nature, continuums do not have clear boundaries or well defined limits. Corps planners should not feel dismay at an inability to clearly locate a situation along this continuum and to label it as risk or as uncertainty. What is important is to identify all situations that fall within the wide region bounding risk and between the extremes of complete certainty or ignorance, in order to consider their important effects in the planning process.

With this warning in mind, we now turn to the task of defining risk and uncertainty analysis.

Risk and Uncertainty Analysis, Assessment, and Management

Though unanimity in terminology does not yet exist in this field, the developing consensus is that risk and uncertainty analysis is a dichotomous process composed of two distinct yet intertwined paths.[7] One path deals with technical determinations and the other with political/management determinations.[8] In response to a Congressional directive, the report Risk Assessment in the Federal Government: Managing the Process (National Research Council, 1983) endorsed the concept that scientific questions about risk should be separated, to the extent feasible, from the policy questions about which risk management steps should be taken. The report describes how science and policy cannot be entirely separated and makes the point that many seemingly scientific issues such as the assumptions made by analysts in a risk analysis have direct relevance to the management decisions.

[7] The literature commonly refers to risk analysis or risk assessment when in fact risk and uncertainty analysis is often meant. For our purposes this is merely semantics and risk and uncertainty analysis, risk and uncertainty assessment, and risk and uncertainty evaluation are the preferred terms.

[8] Tobin (1979) and Lowrance (1976) include among the technical determinations: (1) conditions of exposure, (2) nature of hazard, (3) relationship of exposure to effect, (4) estimate of risk; and among the political determinations: (1) government reviews data and assesses risk (note that this usage will conflict with the usage adopted later in this manual, and (2) government determines risk acceptability.

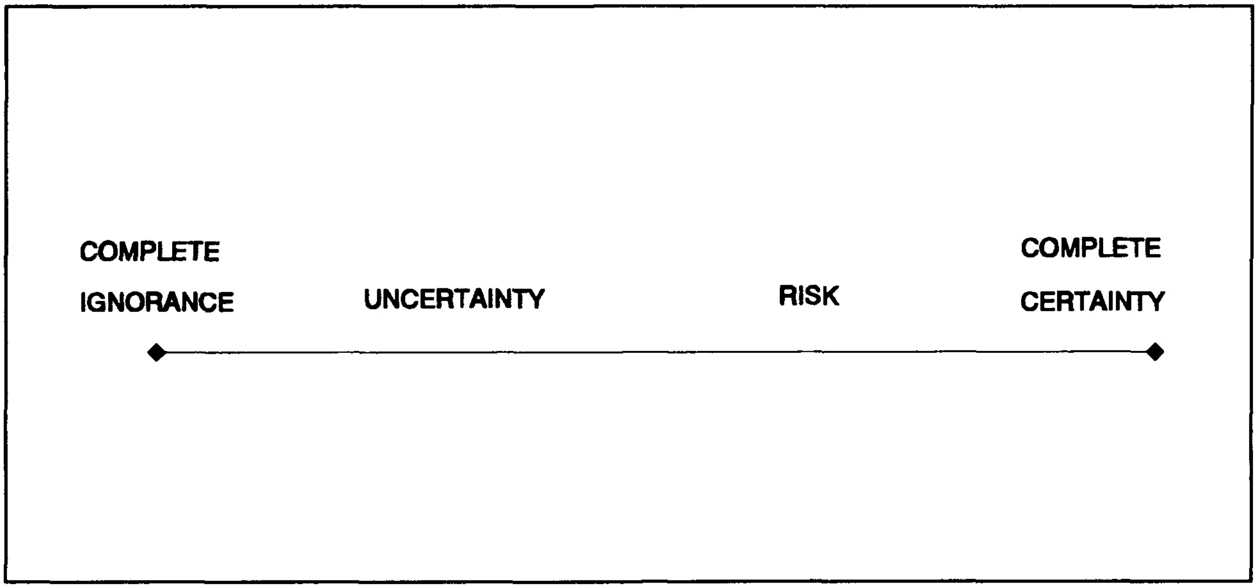

Figure 2-2 Continuum of Knowledge

Though the two-part process is generally accepted, there remains some confusion over what the process is called. A review of the literature reveals that the dichotomous model is sometimes called an assessment consisting of analysis and management while in other instances it is called an analysis consisting of assessment and management. Common usage may be leading to risk analysis becoming the more encompassing term.[9] Gratt (1987) argues cogently for the use of assessment as the more encompassing term, but the tide appears to be running against this position. The National Research Council report to Congress (1983) uses analysis as the more encompassing term and Corps practice to date has consistently used this same terminology.

In the lexicon of Corps planners, "assessment" has come to mean establishing the facts (i.e., the technical determinations path). Its correlate in the EIS framework is "effects." "Evaluation" has come to mean establishing the relative significance, importance or value of the effects (i.e., political/management determinations). Its correlate in the EIS framework is "impacts." To Corps planners this dichotomous relationship is most aptly defined as:

(2.10) Analysis = Assessment + Evaluation

Gratt's definitions sought, more or less arbitrarily, to settle the analysis/assessment argument. His definitions of the concepts are clear. His choice of assessment as the more encompassing term is flawed only by the fact of practice within the Federal government. Hence we will adopt Gratt's concept definitions but with a reversal of terms. Consistent with the Corps' lexicon, evaluation will be used in place of management. The definition has been modified to include uncertainty. The terms are formally defined as follows:

Risk and uncertainty *assessment*:

[9] Gratt emphasizes this point by noting the group seeking a common definition of terms is called "The Society of Risk Analysis."

A detailed examination performed to understand the nature of unwanted, negative consequences; an analytical process to provide information regarding undesirable events; the process of quantification of the probabilities and expected consequences for identified risks and uncertainties.

Relying on the RIMS (1985) definition and the works of Lowrence (1976) and Tobin (1979), we can fashion the working definition of risk evaluation:

Risk and uncertainty *evaluation*:

A decision making/management process of a government, institution, organization, community or individual to protect human life, health, property or the environment from unwanted, adverse consequences by any feasible means including preventive, reactive, and unorganized processes to deal with them.

And again adapting from Gratt (1987):

Risk and uncertainty *analysis*:

The process, including both risk and uncertainty assessment and risk and uncertainty evaluation alternatives, of establishing information regarding acceptable levels of that risk and uncertainty for an individual, group, society, or the environment.

These definitions are consistent with the dichotomous model of risk and uncertainty analysis: the scientific, technical aspects of risk and uncertainty assessment are separate from the political, policy issues of risk and uncertainty evaluation. Risk and uncertainty evaluation revolves around the choices we make as a society about acceptable risks and the attendant trade-offs of costs and benefits in reducing risk. Good risk assessment gives us the information we need, in a form in which we can use it, to address these trade-offs.

This chapter has introduced the concepts of risk and uncertainty and defined risk analysis to be composed, at least conceptually, of assessment and evaluation or management. Chapter 3 will address how risk and uncertainty analysis fits within the framework of the Corps' planning process.

CHAPTER 3

RISK AND UNCERTAINTY ANALYSIS IN THE PLANNING PROCESS

INTRODUCTION

The P&G, promulgated to ensure uniformly applied procedures and approaches and consistent planning by the Federal water resources agencies state that "the Federal objective of water and related land resources project planning is to contribute to national economic development consistent with protecting the Nation's environment, pursuant to national environmental statutes, applicable executive orders, and other Federal planning requirements." This is the underlying goal or purpose of the Corps' planning and evaluation process.

The process consists of a series of steps directed toward formulation of an array of alternative plans. These plans are designed to address the water and related land resources problems and opportunities that are within the purview of the Corps' programs.[10] Selection and ultimately implementation of the best plan, i.e., the one that best serves the Federal objective and State and local concerns, are the goals of the planning process.

Information is the key to success in the planning process. In the rare instance when all necessary information is available there is little need for risk and uncertainty analysis. We can make a certain decision. In virtually every situation, though, we are dealing with risk and uncertainty, and it must be assessed and managed.

In this chapter, risk and uncertainty is considered in the context of the Corps' planning process. The rationale for risk and uncertainty analysis in the planning process is that by improving our understanding of the information we use, we can improve analyses, decision making, communication with the public, and project performance.

OVERVIEW OF THE CORPS' PLANNING PROCESS

Planning is fundamentally a formal evaluation and decision making process. The Corps' planning process provides an orderly and systematic technical evaluation as a prelude to decision making so that decision makers in the Corps and interested Federal, State, and local parties can be made fully aware of the relevant factors that weigh in a decision. These relevant factors include: (1) basic assumptions employed, (2) data and information analyzed, (3) unavailable data and information, (4) areas and degree of risk and uncertainty involved, (5) reasoning and rationale used in formulation, evaluation, and selection.

The Corps' planning process consists of six major steps, as follows:

(1) Specification of problems and opportunities.
(2) Inventory, forecast, and analysis of conditions.
(3) Formulation of alternative plans.
(4) Evaluation of effects.

[10] In reality, most alternative plans are inherently choices among risk management measures as the Corps seeks to deal with the natural hazards present in our environment.

(5) Comparison of alternative plans.
(6) Plan selection.

Each of these six steps revolves around information. Because dependable information is a scarce commodity in nearly every aspect of a planning study, and given the inherent uncertainties in the complex world in which planning is performed, the Corps' planning process is a classic case of decision making under uncertainty.

NATURE OF RISK AND UNCERTAINTY IN THE CORPS PLANNING PROCESS

Throughout the planning process, we seldom know anything with absolute certainty. A host of risk management decision rules or criteria have been developed by the Corps in recognition of this simple fact. Some of these criteria include designation of the probable maximum flood, probable maximum hurricane, underkeel clearance, freeboard, high level of protection in urban areas, etc. These criteria often serve as operating rules-of-thumb or substitutes for formal analysis when we lack better information on which to base a decision.

Through risk and uncertainty analysis we can understand how this lack of certainty in our information affects the decisions we make, from the uncertainty of water demand forecasts, to the vagueness of regional growth objectives and imprecision of cost estimates. It is not as important to precisely label a situation as one of risk or uncertainty as it is to use risk and uncertainty analysis to improve our decisions. This is done through improving our information by: (1) increasing the quantity of information; (2) improving the quality of information; (3) identifying information we would like to have but lack; (4) increasing our understanding of the strengths and weaknesses of the information we do have; and, (5) presenting the results of the analysis in a way that conveys some understanding of our degree of confidence in the information.

To better understand risk and uncertainty analysis within the planning process we can consider the dual-natured aspect of analysis, i.e., the separation of analysis and decision making in relation to the three major interest groups participating in the process. The distinction between assessment (analysis, evaluation) and management (choosing among alternatives) drawn in theoretical discourse blurs somewhat in actual practice. Each of the three interest groups - technical experts (analysts), managers (decision makers), and the public (including specific public interest groups)[11] has a different perspective on risk and uncertainty.

Risk and uncertainty assessment is primarily the domain of analysts and technical experts. Risk and uncertainty management is dominated by managers. Each group has its own priorities and concerns. Their views of what is risky and uncertain can be expected to differ as can their views on what is and is not important. Public interests have viewpoints that frequently differ from, and perhaps conflict with, those of the analysts and managers. In the Federal water

[11] Technical experts in the Corps planning process include engineers, economists, biologists, archeologists, planners, and other technical specialists, the EIS team that may include fish and wildlife experts, etc. Decision makers include the study/project manager, branch chiefs, chiefs of planning and engineering, the District and Division engineers, OASA(CW), BERH, OMB and the non-federal partner in the planning process. The public is broadly defined here to include anyone interested in the planning process who does not fall in either of the other groups.

resources planning approach, public input serves as a keystone to evaluation and selection and is influential throughout the analysis. As we will see, the requirements, attitudes, and perspectives of each group are integral factors in the risk and uncertainty analysis.

The assessment is governed by the need for gathering and analyzing data. Though defining the problems, opportunities, study objectives and potential solutions requires significant public involvement, and frames the evaluation context, the actual analysis level is dominated by engineers, economists, scientists, and other technical experts.

Risk and uncertainty can be found in all natural systems that are typically studied as part of water resources planning, operation and management. They are inherent in winds, waves, tides, currents, rainfall, flooding, and drought. The actions and reactions of both individuals and the collective public are another substantial source of uncertainty. Economic, social, and political institutions and situations can be erratic or volatile, so much so, that it is often difficult to even imagine the range of their possible responses to the existence of natural hazards. Forecasting future conditions is, by its very nature, fraught with risk and uncertainty.

Problems affecting natural resources are becoming increasingly complex. Competition for resources and conflicts among their uses are common. Lack of good information about the natural, economic, environmental, social, and political systems we are dealing with and limited understanding of the available information has prompted the development of a formal approach to risk and uncertainty analysis. Risk and uncertainty analysis is needed to better allocate our scarce resources. The hydrologist does not know Manning's n, a fundamental channel roughness parameter, or the starting elevation of the mainstream channel when calculating stream profiles for a tributary stream. The economist does not know the value of each property in the flood plain nor the damage caused by a flood. Expected annual damage estimation reflects uncertainty about natural and economic systems. The design engineer works without detailed knowledge of foundation conditions. Unit cost estimates are often no more than educated guesses.

Risk and uncertainty assessment is full of issues whose resolution or lack thereof have profound implications for management decisions in subsequent levels of the planning process. Analysts are presented with hundreds, if not thousands, of decisions during the course of a planning study. They are the first and most important decision makers in the process and most of their decisions are subject to varying degrees of uncertainty.

A significant amount of professional judgment must be applied in planning. Whenever there is potential for disagreement among reasonable people about a decision that requires professional judgment that could affect project feasibility or plan selection, the ability and responsibility to make that decision must be carried forward in the planning process for others to decide.[12] Decisions made during the analysis can foreclose options at the decision making level.

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[12] This does not mean that the analyst forsakes his own responsibility to decide. It is a simple recognition of the fact that the analyst cannot know with certainty the value of a variable that may ultimately be important to the selection and implementation of a plan. In such a case, the analyst presents his best estimate of the value but he does not mask the uncertainty inherent in that value by failing to mention other possible values and the impact of those other values being realized on the project and its performance.

It is the analyst's job to identify, clarify, and quantify areas of risk and uncertainty wherever possible, especially for those pieces of information which have a substantial influence on either the choice of an alternative and/or its size and cost. It is the decision maker's job to decide what to do about the identified risks and uncertainties. Once the analyst chooses the value of a key variable it is typically fixed throughout the analysis. Thus, it becomes the analyst's responsibility to learn what decisions he can make without influencing the ultimate decision process either directly or indirectly. This means identifying those factors, variables, assumptions, etc. that are most important to the decision process. This can only be done on a case-by-case basis.

Once the problems have been identified, data gathered and analyzed, and alternative solutions identified, managers begin to dominate the risk and uncertainty analysis in the planning process. Decision makers will face risk and uncertainty issues concerning the problem and its solutions. Many of the issues raised during the risk assessment will remain for the decision makers to manage. They will face new risk and uncertainty issues as they move to integrate the results of the technical assessment with the economic, social, and political realities of the world in which they live.

There will be uncertainty about the effects of the alternatives. Have all the significant potential effects of the plan been identified? Has the risk and uncertainty in them been adequately described and assessed? Is there a consensus that the effects identified are in fact relevant to the decision makers? Have key assumptions, variables, and their values been adequately explained?

If the effects of the plans are reasonably identified, there will surely be uncertainty about the ultimate realization of the plans expected effects. Decision makers will be concerned about the economic feasibility of the plan. Will funds be made available? Will the project ever payout? Political and social acceptability are additional issues.

In controversial studies with strongly held and conflicting points of view there will be uncertainty about the quality of the work and arguments put forth by the various interests. Claims of study bias can be blunted by a fairly conducted and clearly reported risk and uncertainty assessment.

Throughout the planning process, the role of the public and their identification of risk issues and contributions to risk assessment will vary. The "public" is first defined as a group of local citizens looking for help. The public will grow to include other agencies, groups, and institutions. Their concerns will evolve as the nature of the problems become better analyzed and coalitions are formed as the planning process unfolds.

Once we reach the risk and uncertainty management stage, plan selection and communication with the public become of paramount importance. Issues raised earlier in the study can be expected to survive and resurface at this level as concerns of the public come to the fore. Questions of residual risk, acceptable risk, risk transfer, and risk-cost trade-offs all enter the arena as questions of life, health, and safety, and supplant issues such as Manning's *n*, forecast errors, and the likelihood of obtaining the support of elected officials.

Table 3-1 illustrates the dual aspects of risk and uncertainty analysis subject to the influences of three major interest groups. The direct level of influence of each group in each stage is ranked qualitatively by a high, moderate, or low rating. Thus, analysts are most important during the assessment stages of risk and uncertainty analysis. Decision-makers come to the fore during the management stages. The public has a moderate level of involvement in the risk and uncertainty analysis throughout the planning process.

RISK AND UNCERTAINTY ANALYSIS IN THE SIX PLANNING STEPS

The general approach to conducting risk and uncertainty analysis within the Corps' six-step planning process is a micro-level application of the planning process itself. Briefly, the risk and uncertainty analysis identifies potential sources of risk and uncertainty, considers alternatives for minimizing or analyzing the risk and uncertainty, and implements one of the alternatives for dealing with risk and uncertainty. This is done in each step of the planning process.

Essentially, analysts are already performing risk and uncertainty assessment in identifying problems and formulating and evaluating plans. What is often lacking in study documents is an explicit treatment of the assessment work performed. As a result, risk and uncertainty issues are not tracked through the process and little management can be done. Analysts routinely make decisions regarding risks and uncertainties that have profound impacts on the decision makers domain. A good risk and uncertainty assessment with full documentation of its important issues included in the study report will keep the roles of the analyst and decision maker distinct, as they are intended to be. This is essential to the success of the planning process.

The following paragraphs offer suggestions for conducting a risk and uncertainty analysis during the six steps of the planning process.

STEP 1: SPECIFICATION OF PROBLEMS AND OPPORTUNITIES

The key to eliminating uncertainty and analyzing risks is information. It is important to eliminate as much uncertainty as possible about the nature of the problems and opportunities presented. This is done by first understanding how information will be used in planning and in risk and uncertainty analysis and then systematically setting out to collect as much information as is needed. The temptation, if not the tendency, is to define problem statements in terms of

Stage of Analysis	Analysts	Decision Makers	Public
Assessment	High	Low	Moderate
Management	Low	High	Moderate

Table 3-1: Interest Group Influence in Risk and Uncertainty Analysis

solutions and to accept the available information consistent with the "solution-defined" problem, often overlooking other relevant information and views.[13]

Critical elements for a good risk and uncertainty assessment are:

1) problem identification,
2) understanding public views,
3) understanding public attitudes about risk and uncertainty, and
4) establishing specific risk and uncertainty study objectives.

Problem Identification

There are at least two views of every problem. For instance, the public may face a natural hazard and want its exposure to the hazard minimized. The Corps sees the problems in the context of its program, policies, and procedures. These two points of view can present differences that need to be resolved.

When there are fundamentally different ways of looking at a perceived problem it is often easier to agree on a tentative solution than on a problem definition. It is quite common to preserve fundamental uncertainty about the real problems by defining them in terms of their potential solutions, avoiding conflicts over differences in problem identification. For example, a community that has a history of flooding and is experiencing economic decline may confuse the issues of flood control and economic recovery. A flood control project may be seen as the solution to a much more complex problem. To minimize uncertainty in problem identification planners should clearly state the problem without reference to a solution in an objective way that enjoys public support if possible.

Understanding the physical problem is another source of uncertainty inherent in problem identification. Flooding that is attributed to overflowing streams may turn out to be inadequate storm drainage. Tributary flooding may be backwater from the mainstream. People who initially identify the problem will not likely have a full understanding of the natural systems that come into play. Analysts should always look carefully past the public's definition of a problem for corroborating evidence.

Expect and look for uncertainty in the initial assessments of water resource problems. Many future problems can be avoided by not focusing the planning effort or stating the problem too soon or based on too little information. The significance of this step should not be overlooked. Planning objectives are formulated based on the problems identified. The objectives then become the basis for evaluating whether a plan is complete, effective, efficient, and acceptable. Undefined or poorly defined problems lead to bad planning.

[13] This point can best be illustrated quoting from a Corps report that says in part, "... major problems and needs had been identified. The first was to deepen the existing (channel) to 45 feet." Clearly this is a solution, not a problem. It would be very difficult to formulate realistic alternatives to solve a problem that was never really defined.

Public Views

Understanding local concerns is the key to formulating plans that will be acceptable and responsive to local needs. Public views on potential solutions, objectives, and local issues are important to the planning process. Overlooked or misunderstood public concerns are a source of uncertainty that can have devastating effects late in the planning process.[14]

It's important to consider the public broadly when identifying their objectives. It is often easy to identify the objectives of the "official public" or the non-Federal partner who often express their objectives in terms of a solution. It is not always as easy to identify the objectives of the less visible publics and minority interests.[15] Time and money constraints provide an incentive for planners to deal exclusively with a limited and manageable number of parties and interests. Typically, conflicts among less visible groups or individuals is left to local interests to resolve. Such an approach contributes to the uncertainty that an acceptable, implementable plan will be found.

Uncertainty can be minimized by asking people directly how they feel about the problems and potential solutions. Do not rely on passive or one-way communication to identify local concerns. Do not rely solely on the input of the people who show up at public meetings or respond to notices. Minimize uncertainty by systematically seeking to identify the concerns of all groups with a potential interest in the project. Surveys, questionnaires, focus groups, etc. are tools for minimizing this type of uncertainty.

Identifying the range of alternatives proposed by the public presents an early opportunity to limit the uncertainty that the eventual recommended plan will address the public's needs. All imaginable alternatives should be considered at this point and the list of alternatives should not be considered complete. All too frequently the range of alternatives is limited from the outset by the influence of prior studies, the preferences of the non-Federal partner, or political expediency. Even an infeasible alternative favored by a respected community member deserves consideration, perhaps not as a worthy alternative, but as a potential obstacle to consideration of serious alternatives.

Public Attitudes Toward Risk and Uncertainty

There is no such thing as zero risk. No project can completely eliminate natural hazards. There is always some residual risk. Some projects may protect one group but impose new risks on another. There is always a risk, with all projects, that the expected beneficial effects will never be realized. Since it is the public who will live with an implemented project, it is important to ascertain their attitudes toward risk and uncertainty.

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[14] Every Corps District can probably point to a study where the concerns of a group, often environmentally-oriented, were overlooked early in the study process in deference to the views of the local power structure only to have that decision cause substantial problems later in the study. It is far preferable to make the effort to identify the concerns of all groups.

[15] Minority, in this sense, means lacking plurality and does not refer to social or cultural characteristics.

Is there any indication of the levels of risk the community is willing to bear? For example, what level of protection do they want from floods? How much safety do they want in their navigation channels? Do they look at economic benefits as a fact, the money already in the bank? Do they expect complete safety and zero risk? Are they willing to pay for marginal reductions in risk and uncertainty? These are all important questions. Answering them requires planners to determine what the public feels are acceptable risks. Perhaps more importantly it means communicating to the public just what the relevant risks and uncertainty issues and options are, zero risk not being among them.

Risk and Uncertainty Objectives

Following an initial assessment of the problems and opportunities Corps' planners typically establish a set of planning objectives. Some of these, like the NED objective, are common to all studies while others are study specific. If information is not complete, in specifying these study specific objectives, state the assumptions the objectives are based on.

It is important to include specific objectives that deal directly with risk and uncertainty issues. These objectives should address risk and uncertainty issues from the unique perspectives of the public, the analysts, and the decision makers. The risk and uncertainty objectives will vary from study to study, but should always address three vital concepts:

1) acceptable levels of risk,
2) residual risk, and
3) risk transfers.

Careful development of risk and uncertainty objectives early in the study can help guide the risk and uncertainty assessment throughout the study.

Subjective evaluations of problem, solution, and concern statements by the public can be very useful at this stage. However, planners should not hesitate to use statistically valid techniques to identify problems, solutions, and local concerns. Review existing data. Look for sources of measurement error. Consider the age, validity, and completeness of the data. Gather or at least identify additional data necessary to clearly define the problem, public concerns, attitudes toward risk and uncertainty, and study objectives.

STEP 2: INVENTORY AND FORECAST (WITHOUT PLAN CONDITION)

Predicting the future is a fundamentally uncertain process. Many of the phenomena that need to be described or forecast are risky situations.[16] However, the inventory and forecast is a critical step in the risk and uncertainty analysis. Typically, the current approach to this step is to assess without project scenarios and select one as the most probable alternative. The shortcoming to this approach is that this scenario is treated in subsequent planning steps as if it were certain, the only possible future, when that is clearly not the case. In describing the without project condition, then, key variables for the formulation and selection process should be identified. Those that are not known with certainty can affect plan formulation, evaluation, and selection, and should be the focus of the risk and uncertainty analysis throughout the planning process.

The three fundamental elements of the risk and uncertainty analysis in this step are identification of:

1) key risk and uncertainty issues,
2) methods used to address risk and uncertainty, and
3) multiple without project condition scenarios.

Analysts concentrate on gathering and analyzing data in this step. The focus of the risk and uncertainty analysis is clearly on assessment.

Identification of Issues and Important Variables

Specifying risk and uncertainty issues is the first order of business in this step of the planning process. Natural risks and uncertainties arising from the stochastic nature of our physical universe will be inherent in the problems identified. These may include floods, droughts, hurricanes, earthquakes, and so on. In addition to natural sources of risk and uncertainty there are social sources of risk and uncertainty. These arise from the interaction of man with the physical universe and cover such diverse concerns as population growth, land use, zoning regulations, economic institutions, willingness to pay, risk preferences, technological hazards, and pollution. Clearly, there is overlap between the sources of risk and uncertainty: natural events and human activity both impact upon the environment and each other.

Attempts at measuring the risk and uncertainty, whatever the source, are subject to measurement errors, data problems,[17] model and parameter uncertainty, assumptions, and decisions.

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[16] Estimating expected annual damages is perhaps the classic example of analyzing a risky situation.

[17] Some examples are unavailable data, outdated data, data of unknown quality and reliability, incomplete data sets, incomparable data, expensive data, etc.

The objective of risk and uncertainty assessment in this step is to identify what is known with certainty and what is not.[18] It is important that the planner not yield to the temptation to regard everything as uncertain, an exercise sure to end in frustration. It is true that one can always define a context in which everything is uncertain, but perspective is important. The most critical task is identifying "key" variables crucial to the planning process that can affect forecasts and plan formulation and are not known with certainty. Key variables can be data, model parameters, assumptions, and so forth.

For example, what is it that the without project condition scenario is most dependent upon? Population, economic health of the town's main industry, structure values, future development, Manning's *n*, merchants' response to future floods, fleet composition, pilot experience, demand for U. S. grain? An explicit identification of the key variables in some sort of hierarchical order is essential in developing future scenarios.

A key variable is also one whose value or selection could affect project formulation or feasibility.[19] In searching for key variables, no variables should be omitted from consideration. The analysts are the technical experts and the determination of model parameters, assumptions, and the value of variables is rightly within their domain. Nonetheless, when the analyst makes a decision about a variable that other analysts, decision makers, or the public could reasonably disagree with, that variable becomes a key variable if it could affect the project.

Key variables are not restricted to "end use" variables such as interest rates or affluence factors that are openly discussed in Main Reports. Values selected for variables and model parameters normally known only to analysts may be very important key variables. Broadening one's thinking about what a key variable is, is essential for a successful risk and uncertainty assessment.

Technical specialists are often reluctant to admit to those outside their company just how uncertain some of their work is. They may feel justification in such an approach because though it is an educated guess they make, their's is the most educated guess. Who could do better? The experts bring training, experience, knowledge, and judgment that are not available to the layman. This is a compelling argument.

It is largely because they are best qualified to make these judgments that experts should openly display the uncertainty inherent in their work. Often the public or experts from other fields can have just enough information or misinformation to contest a result and create an issue where there should be none. Additionally, the technical expert is typically responsible for a small part of the planning process. He or she has no responsibility for either keeping track of, or managing the cumulative risks and uncertainties of a project. That job that falls to the project manager and decision makers. If risk and uncertainty is to be properly managed, decision makers must have a comprehensive view of just what it is that accounts for the risk and uncertainty in a project. This can only be done with information the technical expert can provide and track.

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[18] Soils, general climate, zoning ordinances, topography, etc. are examples of some things that can be known with certainty.

[19] This includes economic, environmental, engineering, social, political or any other relevant indicator of project feasibility.

Methods for Addressing Risk and Uncertainty Issues

Once the key variables have been identified, methods for dealing with risk and uncertainty become important. The emphasis shifts to measurement of risk and uncertainty. The following discussion addresses the topic of methods in a broad sense. Chapter 5 and several appendices are devoted to a more explicit treatment of this topic.

Analysts must be cognizant of the inaccuracy and uncertainty that is inherent in their tools.[20] Precision in estimation is often confused with accuracy in the planning process. Analysts are as prone to this mistake as decision makers and the public.

It doesn't matter if the model is one of the U. S. Army Corps of Engineers' Hydrologic Engineering Center's sophisticated programs developed for specific water resource applications or a general mathematical or statistical model like the ordinary least squares estimator used in regression analysis, all models have limitations. If the analyst uses a model it is important to invest some time in understanding its limitations. A regression equation yields precise estimates of the parameters of interest but they may or may not be reliable. Even when reliable they are best understood as one in a distribution of many possible estimates.

Statistically and logically valid techniques are required to analyze and minimize risk and uncertainty issues. While study reports are not expected to read like text books or journal articles they should say enough about a statistical technique to justify reliance on the result as a reasonable assumption.[21]

Analysts must know their data. If the data are not exactly what the analyst would like, say so and say why. Options for improving the data should be identified and evaluated, and implemented if warranted.

Multiple Without Project Conditions

The most probable without project condition is, like all forecasts, uncertain. It is not sufficient to present a detailed without project condition without reference to how it was formulated. From a risk and uncertainty analysis perspective the process is at least as important as the result.

Planners should explicitly identify and consider multiple without project conditions. The rationale for this is clear: we can not have the most probable future condition unless we have identified more than one possibility. Plan formulation may concentrate on the most probable

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[20] Moser's paper "Risk and Uncertainty Analysis, Perspectives in Planning" provides an effective explanation of model and parameter uncertainty referred to here.

[21] For example, reports frequently make reference to the fact that a sample or statistical sample was taken to determine some value such as "structure value." This conveys no useful information about how this technique may have contributed to a lessening of the uncertainty about mean structure values in a flood plain. It would be far more helpful to describe the sample design. How was sample size determined? Was it based on the number of observations necessary to yield an estimate within a certain error bound, or was it based on time and money available? One need not be ashamed of the latter case. It is a fact of life. It also will help others understand the extent to which structure value may or may not remain an important variable in the planning process.

condition but alternative scenarios should be carried forward in the planning process. A more robust plan can be formulated and selected by evaluating how various plans perform in alternative futures.

The identification of alternative scenarios should be based on different values of key variables. This is usually the area of greatest concern in the risk and uncertainty analysis. The assessment would then minimize the uncertainty and quantify the risks using methods that are appropriately chosen, applied, and interpreted. At the completion of this assessment, areas requiring further study are identified, risks and remaining uncertainty are described for the important variables, and the implications for the formulation and selection process are identified. Good planning requires that planners avoid giving serious consideration to scenarios that are known to be unrealistic.[22]

STEP 3: FORMULATION OF ALTERNATIVE PLANS (EVALUATION)

With a thorough understanding of the problems and opportunities faced by the community, a clearly defined set of study objectives, and a list of important variables the risk and uncertainty analysis in Step 3 will be substantially easier. The critical elements of the assessment in this step are:

1) formulating a set of alternatives,
2) screening the alternatives, and
3) risk management.

Formulating Sets of Alternatives

We cannot be sure we have the best plan unless a number of alternatives have been formulated. To deal with this very fundamental uncertainty, alternatives have to be considered comprehensively. This means forming true alternatives: considering different levels of protection afforded by incremental heights of a levee, for example, does not alone meet the spirit of formulating alternative plans.

As plans are formulated to meet the planning objectives they should also be formulated to meet the risk and uncertainty objectives. An explicit description of how risk and uncertainty issues affected the formulation of alternatives should be made part of the report.

Screening the Alternatives

All alternative plans are to be formulated to meet four criteria:

1) completeness,

[22] It is not uncommon to find Corps reports that use various without project condition scenarios that assume people will act irrationally in the absence of a Federal project. This assumption is often found in reconnaissance reports for the Corps' continuing authority programs. A representative hypothetical example of this assumption from the Section 14 program would be that if the Federal project with annual costs of $50,000 is not built the local authorities will continue to pay $100,000 per year in emergency repairs to roads and utilities rather than implement the federal project. The cost saving then is used to "justify" the project.

2) effectiveness,
3) efficiency, and
4) acceptability.

At this step in the planning process the extent to which alternatives achieve these criteria is uncertain. The nature and extent of that uncertainty should be examined and addressed.

Is the information available to determine the extent to which a plan accounts for all necessary actions to realize planned effects (completeness)? Do we have what we need to make the plan work? Is all the information available to determine the extent to which a plan alleviates problems and realizes opportunities (effectiveness)? Will it work? Is the plan cost effective (efficiency)? Does the plan meet public concerns (acceptability)? If the answer to any of these questions is no, the shortcomings of the plan should be specified along with alternatives for addressing them.

The screening process should address each plan's contributions to the risk and uncertainty objectives. It should also be used to identify new risk and uncertainty issues and to preserve information about previous ones (e.g., consider the role of the key variables in each alternative).

A good risk and uncertainty analysis will include a preliminary evaluation of the relative degrees of risk and uncertainty accompanying each alternative. To help guide the rest of the analysis it will be helpful to rank the alternatives according to one or more risk and uncertainty criteria. These could be based on the extent to which a plan contributes to the risk and uncertainty objectives, the four criteria above, key variables, or any other relevant dimension of the planning process.

Risk Management

During this step the risk and uncertainty analysis moves from an almost singular emphasis on assessment to include management as well. The screening process necessitates some effort to begin judging acceptable levels of risk. Efficiency may be affected by risk-cost trade-offs.[23] Formulation of alternatives may result in risk transfers.[24] Though final decision making authority does not rest with the analysts, the screening process requires someone, typically the analyst, to make some initial determinations about what is:

1) an acceptable level of risk,
2) an acceptable risk-cost tradeoff,
3) an acceptable transfer of risk, and
4) an acceptable level of uncertainty about completeness and effectiveness.

These are the first formal risk management decisions.

[23] An example is the trade-off between the increased construction cost of widening a navigation channel and the increased risk of delay, grounding or collision (safety costs) associated with a narrower cheaper channel.

[24] Induced flooding that results from construction of a flood control project is a prime example of a risk transfer. The risk to one community is reduced at the cost of an increased risk to another community.

Effective risk management depends on the decision makers' ability to make reasoned decisions on issues and questions that arise during the early steps in the planning process. Careful documentation of these issues is essential in explaining the assumptions on which preliminary decisions were made, in order to allow for their modification or acceptance later in the planning process. A carefully explained process provides decision makers with an initial decision or decision making model to adapt or revise.

STEP 4. COMPARISON OF ALTERNATIVE PLANS - DETAILED EVALUATIONS.

Introduction

The critical elements of the risk and uncertainty analysis in Step 4 are:

1) evaluation of each alternative's contribution to the planning objectives,
2) avoiding the appearance of certainty, and
3) transition in focus to implementation issues.

Evaluation of Alternatives' Contribution to Planning Objectives

By this time the major risk and uncertainty issues should be identified. The emphasis coming into this step is on assessing risk and uncertainty and minimizing uncertainty about project impacts and performance. At this point, it is no longer sufficient to identify areas of risk and uncertainty. Those previously identified areas must now be assessed to aid plan selection. Technical assessment of risk and uncertainty should be essentially completed in this step.

The assessment of risk and uncertainty is accomplished through traditional analytical methods that include, but are not limited to, sensitivity analyses, more/better data, classical statistical analysis, risk/cost tradeoff analysis, professional judgment, subjective probabilities, qualitative forecasts, and a summary of assumptions.

The evaluation of alternatives should address the important risk and uncertainty aspects of each alternative. Uncertain public attitudes and preferences; model, parameter and forecast uncertainty; major assumptions; key variables; risks associated with implementation; and similar issues should be evaluated to identify their affect on alternative plan performance under various without project conditions. The evaluation should identify specific efforts that have been or can be undertaken to reduce these uncertainties.

The evaluation should, whenever possible, include a quantitative estimate of each alternative's contribution to the risk and uncertainty planning objectives. It is expected that these objectives would, in some manner, address the following: minimizing risk to life, health, and safety; minimizing risk to the environment; minimizing residual risks; and, minimizing the uncertainty of project impacts.

Avoid the Appearance of Certainty

Planners and analysts will well recognize the tenuous nature of the assumptions on which they build. It is important to convey that tenuousness in an appropriate manner to decision makers and the public. One way to do this is with careful language. Qualifying statements like "dependent on," "subject to," and "assuming" are most appropriate. While cumbersome language is not advocated, it is wise to qualify uncertain results consistently to avoid the appearance of certainty that results from precision that is not based on certainty.

In many studies, the benefit-cost ratio (BCR) is often the defacto decision variable. No other single piece of information is accorded such eminence. But no BCR should be presented as if it is a certain value. The BCR is a function of numerous random variables, is itself a random variable, and should be treated like a random variable. When reporting the BCR a range of values should be given. The evaluation should clearly describe what it would take for both the maximum BCR and the minimum BCR to be realized.[25] It should also be considered the professional responsibility of the analyst and planner to indicate the circumstances, if any, under which a project may prove to be economically infeasible, i.e., BCR < 1. The possibility of a poor performance by a project is not a fact to be buried amid the arcane language of the technical experts. It is a possibility, the responsibility for which should be shouldered frankly by the decision makers and through them, the public.

Changes in the key variables are likely to have the greatest affect on the BCR. Tracking the key variables throughout the planning process is vital, so that a range of BCRs and the corresponding conditions on which they are based can be displayed for the decision maker.

Initially, presenting a range of values for the BCR will not come easily to analysts, decision makers, or the public. But it is an essential step in communicating the nature of the decision environment we work in. An expected value for the BCR can be estimated using classical statistical analysis, subjective probabilities, or the result of a comparison of the most probable with and without conditions.

Transition in Focus of Risk and Uncertainty Analysis

Though this step begins with an emphasis on risk and uncertainty assessment, as the assessment nears completion the interface between assessment and management comes to the fore. The focus becomes one of implementing the project. The first step is, of course, communicating the evaluations performed on the formulated plans.

At this point, particular attention needs to be paid to potential adverse impacts of the plan. Residual risk, increases in existing risks, creation of new risks, and transferred risks must be considered. Once the assessment of such issues is complete these risks must then be managed.

STEP 5: COMPARISON OF ALTERNATIVES - DETAILED ANALYSIS

This step is critical in the risk and uncertainty management process. At this point the planner has to make sense of all the work and formulation that has been done. The cumulative impacts of risk and uncertainty on the performance of alternatives must be summarized in a manageable and reasonably comparable way.

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[25] This analysis can be as sophisticated as the circumstance warrants. At a basic level, this evaluation should be based on comparisons of with project scenarios for different values for key variables to the various without project scenarios. The maximum and minimum BCRs yielded by this analysis could define the range.

The principal elements of the risk and uncertainty analysis at this step are:

1) quantifying the cumulative effects of risk and uncertainty,
2) comparing the risk and uncertainty aspects of the alternatives, and
3) displaying the results.

Cumulative Effects of Risk and Uncertainty

From the beginning, the planners' risk and uncertainty analysis efforts should be directed towards evaluating the cumulative effects of significant areas of risk and uncertainty on the alternative's ability to solve problems and achieve opportunities. This is a pivotal step in the analysis. Neither the physical nor economic performance of any alternative is certain. The degree of certainty with which each alternative can be expected to meet its projected performance is directly related to the risk and uncertainty in all the key variables used in its formulation. The planner must bring all the risk and uncertainty analysis together in a meaningful and understandable way. Cumulative levels of risk and uncertainty associated with the alternatives must be identified.[26]

It may be helpful at this point to come back to the notion of a risk and uncertainty assessment as a search for better information to improve the decision making process. The greater issue of information encompasses risk and uncertainty and so it is useful to consider the information we had, the information we needed, the information we gathered, the information we developed, the information we still lack, and what this all means for project performance.

Comparison of Risk and Uncertainty Aspects of Plans

Because aspects of risk and uncertainty are likely to be different for each alternative plan this step should focus on a comparison of risk and uncertainty evaluated in previous steps. In comparing evaluations of alternatives, planners should clearly document the use of subjective judgment in determining the impacts associated with implementation of that alternative. Where objective estimates of risk have been used the associated technique should be described. Summarize the major assumptions used in the evaluation of alternatives, clearly describing the uncertainty associated with each of them. Major areas of risk and uncertainty that need to be considered in the final decision making process should be identified.

Displaying Results of Comparison

Comparing the cumulative effects of risk and uncertainty on the alternatives' abilities to contribute to planning objectives and project performance is a significant piece of work. Displaying the results is absolutely critical to the risk and uncertainty management task.

The use of clear and concise summaries is indispensable. Imaginative use of tables, figures, displays and formats, can also be helpful. It is to this step that the decision making prerogatives of the decision makers must be preserved. It is in this step that they must be clearly communicated. Decision makers must be presented with a clear understanding of what is

[26] Objective measures are preferred whenever they are feasible. In their absence, subjective measures such as most certain or least certain are useful.

uncertain in each alternative and what the implications of that uncertainty are. They must know what the risks attending each alternative are and the trade-offs among them. They must also know what decisions they are expected to make in addition to plan selection.[27] If these points are not effectively communicated the best risk and uncertainty analysis will have been for nothing.

The decision document for sediment control of Mount St. Helens eruption debris prepared by the Portland District[28] provides a good example of current Corps efforts to display risk and uncertainty information is a useful way.

STEP 6: PLAN SELECTION

By now, the risk and uncertainty assessment is essentially complete. This step of the planning process belongs to risk and uncertainty management

Risk and Uncertainty Management

The risk and uncertainty assessment should highlight just where political and social judgments have to be made. The assessment must avoid burying these judgments in the interstices of an incomprehensible planning process.

Two basic issues will always be presented to decision makers. The first, more uncertainty-oriented, is whether or not the results of the problem identification, forecasts of alternative futures, and formulation and evaluation of plans are credible. It is here that issues concerning data, model and parameter uncertainty, and other key variables are resolved. Uncertainty is important at this point to the extent that assumptions made in lieu of certain information are important to project feasibility and selection. The more contested and controversial the assumption, the greater its importance to decision makers.

The second issue concerns the more classical risk management focus. It is likely that the emphasis of the decision makers will be on risk management. To raise the appropriate issues the assessment should develop a series of questions or useful taxonomies relevant to the risks presented by the alternatives.

Some general questions to help guide the management of an identified risk might include the following:

1) Is the risk significant?
2) What are the mitigation alternatives?
3) What are the costs and benefits?
4) What are the legal, social, and political ramifications?

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[27] The decision maker is not expected to decide what the proper Manning's *n* value or structure value are. This is the analysts job. However, it may be important for the decision maker to know what had to be assumed to arrive at the *n* value or structure value, if that is a matter of uncertainty critical to the project's formulation or feasibility.

[28] U.S. Army Corps of Engineers, Portland District, "Mount St. Helens, Washington: Decision Document (Toutle, Cowlitz and Columbia Rivers)," October 1985.

5) What are the implementation and performance issues?

A good assessment will present a clear summary of relevant information and recommendations to help decision makers answer these or other relevant questions.

In some cases it may be helpful to develop risk taxonomies to present risks to decision makers. For example, risk might be classified in the following way:

1) situation in which the hazard or risk is encountered (e.g., risk of collision during a navigable pass in-channel, or risk of grounding);
2) cause of the hazards or risk (e.g., channel width, turning radius, channel depth, aids to navigation);
3) kind of hazard or risk (e.g., economic loss, environmental damage, threat to life, health and safety); and
4) geographic/political division of risk management responsibility (e.g., within city, by state, Coast Guard, Corps, pilots).

Methodologies to integrate judgmental aspects with empirical approaches to evaluate trade-offs among risk alternatives are not yet well-developed. This series of questions and taxonomy are merely suggestive of the general ways risks can be presented to decision makers. What is of paramount importance is that they have as much useful information as is available, presented to them in a manageable and efficient form.

Once a plan is selected, the role that risk and uncertainty played in the selection process should be described in detail. This description should address the risk and uncertainty objectives, major risk and uncertainty issues, and the cumulative effects of risk and uncertainty. Particular attention should be given to ways in which to display and summarize key information, assumptions, and conclusions.

SUMMARY

This Chapter notes that risk and uncertainty are inherent in each of the six steps in planning a water resources project. In conducting a planning study, the planner needs to recognize the risk and uncertainty issues and provide provisions for addressing them prior to initiation of the study. For each of the steps, the potential problems are described and specific suggestions are made concerning how to address risk and uncertainty.

CHAPTER 4

POTENTIAL SOURCES OF RISK AND UNCERTAINTY BY PROJECT PURPOSE

INTRODUCTION

Chapter 3 presented a general discussion of risk and uncertainty in the broad context of the Corps' six-step planning process. This chapter looks at potential sources of risk and uncertainty by the Corps' project purposes as identified in the P&G.

The P&G evaluation steps provide a good, though limited, framework suggesting likely candidates for designation as key variables and relationships. Identifying potentially important variables is the purpose of this chapter. Inclusion of a variable in this chapter is not prima facie evidence that it is important in any particular study. Conversely, neither is the exclusion of a variable evidence that it is unimportant. First, risk and uncertainty issues common to almost all Corps projects are discussed. These include risk and uncertainty objectives in planning, environmental issues, institutionalized uncertainty, and basic components in project design. Sources of risk and uncertainty specific to various project purposes will then be addressed.

RISK AND UNCERTAINTY OBJECTIVES

It has been suggested that specific risk and uncertainty planning objectives should be identified during Step 1 of the planning process. While specific all-purpose objectives cannot be identified there are some concerns applicable to almost every project.

Problems that deal with natural or man-made hazards involve some probability of that hazard's occurrence. Whenever plans are formulated to mitigate the risk of a hazard, it is appropriate to identify both an acceptable level of risk and an estimation of residual risk with project implementation.

The transfer of risk or the creation of new risks is also important. Whether objectives are stated in terms of avoiding such situations, quantifying them for purposes of trade-off analysis, or dealing with them in another manner depends upon the situation.

The principal "generic" objective dealing with uncertainty is to minimize uncertainty in key variables and parameter values. This, very simply, is an analytical commitment to provide the best information available to the decision maker.

ENVIRONMENTAL ISSUES

Many of the problems and opportunities presenting themselves to Corps' planners will involve significant and complex environmental issues. In addition, the alternatives formulated may often involve environmental impacts that present serious new assessment and management problems in the areas of life, health, and safety; ecological attributes; cultural attributes; and aesthetic attributes.

Identification and measurement of environmental impacts are among the most difficult tasks in water resources planning. The complexity of environmental systems, a dearth of data, and the limitations of science and technology render many environmental issues fundamentally uncertain. The assessment of habitat, wildlife populations, wetlands functions, recreation usage, open space, and ecosystem values and issues, to name a few, entail tremendous uncertainty by the nature of their complexity. The need to forecast, describe and evaluate complex effects requires the use of habitat evaluation tools (e.g., HEP, HES, WET) that are in themselves subject to extensive model and parameter uncertainty.

Chapter III of the P&G presents EQ procedures. This detailed presentation suggests both the complexity of the problem and places to look for uncertainty in the procedure.

<u>PROJECT DESIGN</u>

There are some features common to the design of all projects that may be sources of risk and uncertainty. The most common problem is, of course, uncertainty that results from a lack of detailed information.

Most engineering studies involve foundations and materials, surveys, and design work to varying extents. Hydrology and hydraulics are important in a wide variety of Corp studies. The key variables in each of these areas should be identified. Project elements that would ordinarily be the subjects of design memoranda are top candidates for key variables. These variables are important for understanding project performance and costs.

Cost estimating is an area of particular concern. Costs are obviously important to project feasibility, yet they often contain substantial uncertainty. Quantities may be based on preliminary design and simplifying assumptions. Sources of materials may be a matter of speculation until late in the design stages. Unit costs are often based on bid prices for contracts that bear little similarity to the project at hand.

Contingencies have traditionally been used to address the uncertainty inherent in cost estimates. Knowledge about specific sources of uncertainty should not be hidden in the contingency category. Those variables that contribute most to the uncertainty about costs and the need for contingency allowances should be explicitly identified.

Assumptions used to generate operation and maintenance and major replacement costs should be explicitly displayed. The effects of alternative assumptions on these costs should be considered.

Uncertainty concerning the potential construction schedule should be specified. This effort will make it possible to identify a more realistic base year and to compute the costs of interest during construction more accurately.

Staging the construction of project elements introduces potential uncertainty and risks. Staging of projects can result in excess or insufficient capacity to produce project outputs.

MUNICIPAL, INDUSTRIAL, AND AGRICULTURAL WATER SUPPLY

Identifying existing and future sources of water supply requires considerable risk and uncertainty analysis. Sources of uncertainty are likely to include inadequate data or understanding of one or more of the following: streamflow records, precipitation records, evaporation rates, inflow, runoff, percolation rates, releases, spills, available groundwater resources, low-flow sequences, firm yield, critical drawdown periods or cycles, design drought frequency, water losses in the distribution system, quantity and quality of return flows, general water quality, the relationship between groundwater and surface water, and available reservoir storage. In addition, there is considerable model and parameter uncertainty involved in the analysis of these data and relationships.

Estimating existing and future demand for the water is equally uncertain. Demand can increase because of growing population, changing development, or changing water use patterns. Identifying needs by sector requires detailed information about the use of water and determinants of demand (particularly price) for that use. For example, residential demand in gallons per capita per day varies widely depending on indoor use versus outdoor use and population. There is bound to be great uncertainty in determinants of demand for indoor and outdoor water. Income is one example. Higher incomes may lead to more outdoor pools or more water intensive landscaping. Other variables such as population growth, number of people per household, climate, and state of the economy may be important in determining demand. Collecting reliable data or forecasting these values is also subject to uncertainty.

Commercial usage depends on the number of office buildings, stores and warehouses as well as the type of businesses. Industrial use varies widely from industry to industry and even by technology within an industry. Future industrial development may be a key variable in a growing area.

Public usage of water depends on the number of parks, golf courses, public pools, fountains, hospitals, churches, schools, and other municipal facilities. Indoor and outdoor uses are also important distinctions for public water use.

Agricultural water use depends on water law, management agreements and institutions, climate, soil, crop mix, growing season, vegetation, distribution losses, and farming practices. One of the principal determinants of usage is demand for crops. In some cases this demand may be relatively small and local. In others cases, international markets are relevant. Changes in prices, production costs, crop yields, land use trends, cropping patterns, crop water requirements, farm yields, consumptive usage, return water, and short run climatological problems comprise only a short list of the types of variables that may ultimately be important to plan formulation. Any of these determinants of usage could be an important variable in a given study.

Forecasting these and other variables introduces a new and significant issue of model and parameter uncertainty. The difficulties become magnified when differences in seasonal demands and changes over time are taken into account. Reliance on farm budget analysis or land value analysis to value agricultural water supplies presents a number of unique data problems. Estimating economic profits by specifying an opportunity cost for all inputs is a controversial and inexact task.

Potential solutions to water supply problems are replete with uncertainty and risk issues. Some important variables are alternative cost estimates (because the marginal cost of water is rarely available), the reliability and remaining life of existing structures, and reliability of yield from potential sources of supply. Reservoir operational studies have substantial data and analytical requirements. Historical or synthetic streamflow records for the site are necessary. Various capacities and a complete range of combined demand patterns must be analyzed. Yield-capacity and cost-capacity relationships are very sensitive to the major assumptions that go into them.

One of the most obvious risk analysis problems is determining an acceptable level of risk of occasional shortage. When water supply solutions involve dams, the entire gamut of dam safety issues comes to the fore (see the Institute for Water Resources' "Socioeconomic Considerations in Dam Safety Risk Analysis" for a more complete treatment of this issue).

FLOOD CONTROL

Flood control analysis is often offered as a classical example of risk assessment. The computation of expected annual damages is a direct application of the expected risk concept. While the hydroeconomic model used to estimate expected annual damages is an effective risk assessment tool, there is considerable uncertainty encountered in its construction.

Understanding the physical nature of the flood problem, its magnitude and probability of occurrence, is one major source of uncertainty. Identifying the consequences of floods is a major source of uncertainty encountered in the land use analysis. Classical risk analysis lends itself directly to a number of flood control risk assessment problems such as quantifying risks and risk transfers, and to risk management problems of determining acceptable levels of risk and risk-cost trade-offs.[29]

The stochastic nature of flood events means that flood control projects involve a great deal of risk and uncertainty. The major sources of hydrologic uncertainty are:

1) data availability;
2) data error;
3) accuracy and imprecision of measurement and observation;
4) sampling uncertainty, including the choice of samples and appropriate sample size;
5) selection of an appropriate probability distribution to describe the stochastic events;
6) estimation of the hydrological and statistical parameters in models;
7) low probability flood extrapolation, e.g., tail problems of frequency curves;
8) modeling assumptions; and
9) the characterization of river basin parameters.

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[29] An unpublished report, "An Integrated Sensitivity Analysis Procedure for Evaluating Risk and Uncertainty in Local Flood Damage Alleviation Projects" by the Institute for Water Resources does an excellent job of exploring the sensitivity of expected annual damages to changes in various assumptions common to most flood control analyses. Much of the material in the discussion of flood control is taken from the draft version of this report.

Flood frequency analysis typically relies on one of two methods. First are data-intensive methods that include statistical data fitting. Second are derived distributions used in regions that lack hydrologic records. Data-intensive methods use the Log-Pearson Type III distribution, mandated for use in flood frequency analysis by the U. S. Water Resources Council.

Flood return periods are generated by the data sample size and the distribution chosen to represent the data. Frequencies of flood events, particularly extreme events, are very sensitive to the choice of distribution. With so much professional disagreement over the best distributions, blind reliance on Log-Pearson Type III will limit the usefulness of risk analysis for flood control. Even when this distribution is best, the values of the three parameter estimates that make up this distribution are usually uncertain.

Frequencies of future flood events are subject to professional disagreement. Future watershed development, climatic trends, randomness of events, and other similar factors are extremely difficult to forecast with any degree of accuracy.

Hydraulic information is subject to potentially serious aggregation errors. For instance, estimating flood profiles along a stream involves aggregating areas into segments along the reach. Invariably such methods require the use of a geographic centroid or focal point to represent the entire segment. Variations in surface conditions, runoff, roughness coefficients, hydraulic jumps, etc. can be over or under emphasized according to the aggregation method used.

Potential sources of uncertainty in the hydraulic analysis with significant impacts for project costs and benefits are too numerous to mention. A natural starting place to identify the specific sources of uncertainty would be to examine the parameter values used in the HEC programs common to most flood control studies. In general terms, the major sources of uncertainty can include rainfall analysis, development of synthetic storms, standard project and probable maximum storms, antecedent moisture conditions, soil type, land cover, hydrograph analysis (particularly difficult for ungaged basins), rainfall-runoff relationships, watershed development, flood hydrograph routing, use of steady flow and rigid boundary assumptions, number and quality of cross sections, energy losses and Manning's roughness coefficient, and flow around obstacles. Flood stage is one of the most important determinants of project benefits and costs, yet it is subject to potentially huge impacts of cumulative uncertainty.

A problem in ultimately describing the flood problem lies in the analysts' inability to handle many of the dimensions of the flood problem. Flood damage is generally treated as a function of the depth of water. In reality, the duration of the flood, sediment load, energy (waves, velocity, etc.), presence of ice, debris, and water quality can be even more important than depth.[30] Accurate delineation of different frequency flood plains on maps can be a very uncertain venture. With limited analytical tools and techniques for estimating the effects of these problems on the hydraulics and damage estimates, the basic inputs to the expected annual damages model are very uncertain.

If the hydrology and hydraulics are made difficult by the stochastic nature of the events under study, land use analysis is no easier because of its substantial data requirements and

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[30]Attempts have been made to incorporate these influences on flood damage although typically in an *ad hoc*, arbitrary manner.

reliance on unpredictable human behavior. The purpose of the land use analysis is to estimate the damages that will occur as a result of different flood events, both now and in the future. An inventory of the number, type, value, and susceptibility to flooding of structures in the flood plain is an essential part of the flood control analysis. An inventory may be based on a sample of the population. In such a case the statistical design of the sample is extremely important to the validity of the results obtained. In practice samples are often biased, their design frequently being based on time and money constraints rather than the statistical properties of the sample.

Property values are required for damage estimates in most analyses. The benefit standard is the willingness of people to pay to avoid the damages that would occur without flood protection. The estimate of that willingness to pay is based on the value of a structure. There is a great range in reliability of the data used for this purpose. Tax assessments, comparable sales, income capitalization, and construction cost indexes are the most commonly used methods to estimate property values. Some of these methods capture the value of the real resources that could be lost or damaged in a flood better than others. Methods that are based on a replacement in-kind estimate of value or depreciated replacement cost are most compatible with the benefit standard and recommended by P&G, yet they are not always used.

Sales data are particularly worrisome because of the differences in long run and short run equilibria. Information about the flood hazard is assimilated by the market in widely varying ways, depending on the recent flood history. Actual market data, though preferred in many economic analyses can lead to intractable practical difficulties in many cases.

In addition to uncertainty concerning the value of property there is considerable uncertainty about the value of contents, the flood stage at which damage begins, first floor elevations of structures, responses to flood forecasts and warning, flood fighting efforts, cleanup costs, and business losses.

Depth-percent damage curves are among the most important and least exact data in benefit estimation. These curves express dollar damages resulting from varying depths of water based on some percentage of the value of structure and contents. The basis for such relationships is often poorly understood and weakly based in factual knowledge. Despite their obvious importance to the benefit estimates they are rarely scrutinized, largely because they are difficult relationships to document. This is, of course, precisely why they should be assessed and analyzed more carefully.

The dollar damages that would result from a given depth of water in a building is a random variable. The estimate of the value of this variable is conditioned on the assumptions made when damages are calculated. Though the structure value and water depth may be constant, the damage may depend on the amount of warning time; the time of day, week, month or year the flood occurs; the availability of labor, special riggers, equipment or trucks needed for flood fighting; or the availability of off-flood plain storage for evacuated goods and equipment.

The hydroeconomic model used to develop expected annual damages is based on discharge-frequency, stage-frequency, and stage-damage curves used to develop a damage-frequency curve. The discharge-frequency relationship may be well understood, based on historical data. But analysts need to be cognizant of the fact that the estimate of the stage associated with a given discharge is a random variable that could take any number of different values. Winds, waves, sediment, time of year, and random river jams all affect the stage a discharge will obtain at a given point on the river. Likewise, the estimates of damages for a flood stage are random variables.

The land use analysis is subject to the same aggregation errors that can plague the hydrology and hydraulics. Future land use estimation is subject to the difficulties presented by all forecasting methods.

Formulation of flood control projects may result in risk transfers. Property protected by the project has its risk reduced, but the project may result in increased risk of flooding for other property. Local flood protection projects may induce flooding in communities up-, down-, or across-stream from the project. Reservoirs may create risks for property not previously at risk or may dramatically alter the nature of the risk as a result of potential dam failure.[31]

Risk management for a flood control project requires a determination of an acceptable risk. Absolute protection from flooding is an unachievable goal. A residual risk of flooding will always exist. Determining an acceptable level of residual risk is a critical plan formulation decision. This decision can be aided by a risk-cost analysis that presents the costs of marginal decreases in risks and the benefits of that decrease. This would include traditional benefit and cost analysis more clearly focused on the issue of residual risk. More importantly risk-cost trade-offs must often include risk objectives that are not readily monetized.

HYDROPOWER

Hydropower projects involve many of the same hydrologic and hydraulic analyses mentioned in previous sections. Unique hydropower study elements include analysis of the power grid, operation studies, demand for electric power, and most likely alternative sources of power.

Hydropower studies require identification of the existing and future power grids relevant to the study area. With the growing complexity of interconnections and agreements it is increasingly difficult to identify a system for analysis. Available generating resources, power system contracts, treaties, plant retirements, and new plants coming on line must be identified. Environmental restrictions affecting existing and future generating resources of all types need to be addressed, as does the possibility of changes in these environmental restrictions.[32]

Operation studies combine the uncertainty of stochastic events (the hydrologic cycle) and unpredictable human behavior (competing and complementary demands for water). Though basically accounting problems, operation studies require detailed knowledge of inflows, outflows, losses, and changes in storage. These studies can become very complex when they deal with a system of reservoirs and multiple uses for the water. Mass curve analysis, power curve

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[31] Although dam failure presents the most familiar project failure scenario that alters the nature of the flood risk it is not the only one. Levee and floodwall LFPs may induce more intense development in the flood plain due to a false sense of security provided by the physical presence of the project. If an LFP alters flood plain development this represents the creation of a new risk or at least the modification of an old one.

[32] For example, future legislation to address acid rain or other problems should be taken into consideration when they can be reasonably expected.

requirements, and rule curves can embody extensive and complex uncertainty with critical implications for project costs, water use, and power generation.

Estimating demand for electric power is beset by the uncertainties inherent in any forecasting activity. Power loads and annual peaks and energy demands by season and sector are two important elements of the analysis likely to be uncertain. Power market surveys require knowledge of existing prices for power and energy, estimates of population and market changes, and anticipation of technological changes. Differential costs for base and peaking energy are often uncertain. The relationship of price to marginal cost is not always clear. Effective handling of the uncertainty inherent in energy and power values is complicated by the fact that these values are often provided by analysts from other agencies with no direct responsibility for dealing with the risk and uncertainty in a project.

The most likely alternative cost method for estimating project benefits provides a theoretical upper limit on willingness to pay that may overstate true willingness to pay. Recognizing this possibility, it is particularly important that the most likely non-federal alternative be realistic. Defining an alternative that provides similar service to the hydropower project is complicated by the need to determine what is a realistic alternative and what constitutes similar service. Alternative costs for generating capacity and energy costs are both necessary in this analysis. Because cost estimates for alternative projects may not be available in detail comparable to those developed for the proposed hydropower project, sensitivity analysis or other techniques are needed to deal with the resultant uncertainty.

NAVIGATION

Though inland and deep draft navigation differ in many important aspects they are similar enough that potential sources of risk and uncertainty can be discussed in general terms for both. Project design, construction and operation and maintenance costs, dredged material, commodity forecasts, and fleet composition are significant elements common to any navigation project. Material presented under inland navigation may well be applicable to deep draft navigation and vice versa.

Inland Navigation

Project design for a navigation project may involve formulation of the optimal depth and width of a channel as well as turning basins, anchorage areas, and channel geometry in bends. Optimal determinations of these and other project parameters are possible only after considerable engineering, safety, economic, and environmental analyses.

Design of a project must also take into account many diverse stochastic considerations in addition to the normal hydrologic and hydraulic work. Ice, drought, bank stabilization, currents, fog, and waves are some examples of these.

Inland navigation projects often involve the rehabilitation, replacement, or construction of locks and dams. Design may involve multiple use issues. For inland navigation the critical design question is the optimal capacity of the lock. Delay is a key concept in lock and dam design. It can result from natural causes such as ice, fog, and flood; human activity such as maintenance; or mechanical or structural malfunctions. The frequency of these various events lends itself readily to classical statistical analysis.

Economic analysis for major rehabilitation of existing locks and dams requires quantification of the probability and consequence of the failure of the lock to operate in the future. Few serious failure events have ever been observed. The possible failures range from an increase in frequency of nuisance type lock closures to the low probability-high consequence type events such as loss of pool. Low probability-high consequence event analysis presents formidable analysis problems.

Dredging and dredge material disposal are the primary costs of channel improvement. The removal and disposal of dredged material can be the source of numerous environmental concerns and the possible creation of new risks to fragile ecological systems.

Commodity forecasts have long been a significant and controversial source of uncertainty in navigation projects. With inland navigation studies it can be difficult to identify the ports of origin and destination with any certainty. The commodities that move into and out of a port must be identified as well as the total tonnages of each and the size of average movements. The P&G place the additional requirement of distinguishing new movements from existing movements, change in mode movements over the same route, and new origin-destination pairs. Commodity forecasts are generally limited to 20 years. Again typical forecast uncertainties arise, but the 20 year restriction may be inappropriate. Twenty year projections may be too long, or in some instances too short. In any case the appropriate growth period is clearly uncertain.

In addition to forecasting commodities, analysts must anticipate changes in navigation technology and practice as well as forecast changes in fleet composition. New tugs may lead to new tow configurations or changes in barge design. A critically important consideration in analyzing fleet composition is the operating costs of the vessels. These costs are currently estimated for Corps-wide use by the Institute for Water Resources and are affected by input prices (fuel and labor), prices of other goods (rail rates), and the general state of the economy (e.g., excess supply of or demand for barges and tugs). The costs are provided to field offices, but they have limited access to information that would better define the uncertainty inherent them.

In considering the least costly alternative form of transportation, published rail rates are generally used. It has long been recognized that these values bear little relationship to long run marginal costs. Their continued use could misallocate resources. Increasing reliance on contract rates makes published rates, when available, even less reliable than before. This represents an area of serious uncertainty that should not be overlooked in at least a sensitivity analysis.

Deep Draft Navigation

Design of deep draft navigation projects involves many of the same engineering, economic, and environmental analyses and the attendant risks and uncertainties as inland projects. However, other issues are of greater concern in deep draft projects.

Safety is a particular concern for deep draft navigation. Channels must be deep enough to avoid groundings, and wide enough to avoid collision. Because absolute safety can't be guaranteed, risk-cost trade-offs should be part of any project design optimization. Assessment of in-channel collisions often entail low probability-high consequence event problems. If collisions have not occurred it may be difficult to extrapolate probabilities of their occurrence. Ports trafficking in liquid natural gas or other volatile or toxic commodities may experience consequences that are very uncertain and difficult to describe, much less quantify. Quantifying the consequences of these low probability events is likewise problematic. The true costs of the Exxon Valdez oil spill in Alaska may never be known. Speculative events are even more difficult to quantify.

Direct and indirect costs of dredging channels are the primary costs of deep draft navigation projects.[33] Both the quantity and quality of material to be dredged are important factors to be considered in determining these costs. Uncertainty about both, thus influence project formulation. Channel design dimensions such as side-slopes depend on the quality of information available on materials. A hard bottom can have steeper slopes and therefore fewer cubic yards of material to remove than a soft bottom that requires gentler slopes. The quality of the dredge material also has a significant effect on the costs of handling and disposal. Potential environmental impacts increase as dredge material quality is degraded and quantity is increased. Grab samples may result in less certainty about side-slopes/dredging requirements/project costs than core samples.

Commodity forecasts are, again, a major source of uncertainty. Recent experience teaches a valuable object lesson. During the energy crisis of the 1970s world demand for U. S. coal was booming. Many forecasters and port authorities thought this strong demand could go nowhere but up. History has proven the inaccuracy of forecasts and the volatility of world commodity markets.

The gradual recognition of the increasing interdependence of the world's national economies, growing concern with the "twin deficits problem" of our national debt and trade deficits present analysts with a substantial challenge. Discerning what these developments mean to world demand for U. S. goods and U. S. demand for imports is highly uncertain.

It is not just national economies that are interdependent. In recent years Corps' analysts have more and more recognized that U.S. export and import activity is a very competitive business. Commodity increases at one port often come at the cost of commodity decreases at another port. Market shares are constantly changing. This fact cannot be denied in a complete analysis.

Fleet composition is one of the least certain aspects of a deep draft project. While existing fleet composition is relatively easy to document, it is extremely difficult to project future fleet composition. Future fleet composition depends on technological trends such as wider beam, shallower draft vessels and a movement toward less labor-intensive loading and off-loading technologies. Changes in land-side technology, such as the advances in handling and moving container cargo, can be as important as changes in navigation technology for future fleet composition. Assumptions about future fleet composition go a long way toward determining transportation cost savings and cannot be overlooked as important sources of benefit uncertainty.

[33] Direct costs include the costs of dredging and disposing of the material. Indirect costs involve utility and other relocations.

The future fleet depends on ever-changing itineraries of shipping lines, port development in foreign countries and competing American ports, excess supply or demand of shipping capacity, world commodity prices, and a complex host of other factors. With multiple forecasts being made for each of these factors comes cumulative uncertainty. When commodity forecasts are combined with forecasts of vessel size, the potential for compounding errors due to unrealized forecasts is not hard to imagine.

Vessel operating costs are another source of potential uncertainty. Deep draft vessel costs prepared by the Institute for Water Resources are subject to the same uncertainty and problems that inland waterway vessel costs are. The nature of this uncertainty is generally neither understood by nor available to field personnel.

COMMERCIAL FISHING

Commercial fishing projects can encompass many of the same risks and uncertainties presented by other navigation projects. Because of their focus on the harvesting of commercial fisheries, they also add a few unique considerations.

Supply and demand for the commercial fisheries harvested at a project need to be analyzed. There is uncertainty surrounding many of the determinants of supply and demand. Morbidity and reproduction rates for the fishery, available habitat, effort (number of vessels, fishermen, or equipment), technology, water quality, price of fish, and fishery regulations affect the supply of fish. In individual studies the factors affecting these and other determinants, particularly environmental influences, are also uncertain.

Reliable estimates of harvest costs are often difficult to obtain. Changes in marginal costs are not always identified. Determining normative market prices of fish is troubling when prices vary so drastically from time-to-time and place-to-place. Though demand for the fishery depends primarily on price, analysts must remain aware of potential fishery issues that could affect demand.[34]

Identifying the most probable future conditions both with and without a project is very difficult with a dynamic population of commercial fish. The effects of overharvesting a common property resource that may be simultaneously facing declining habitat should not be overlooked.

The P&G currently suggests that the opportunity cost of management be valued at 10 percent of the variable harvest costs. This is an example of institutionalized uncertainty that has no basis in fact. Project sensitivity to other estimates should also be examined. Current methods of estimating reductions of damage to vessels should also be subjected to risk and uncertainty assessment methods. They are rarely rigorously determined at present.

[34] An example was the State of Massachusetts' 1988 ban on the use or sale of Maryland clams in local markets because of unacceptably high bacteria counts found in the Maryland clams.

SUMMARY

This chapter has identified some of the more prevalent risk and uncertainty issues inherent in Corps projects. Though by no means a complete list, it can guide the planner in thinking about risk and uncertainty problems that are sure to be unique to any one project.

CHAPTER 5

TECHNIQUES FOR DEALING WITH RISK AND UNCERTAINTY

INTRODUCTION

Although people often differentiate between risk and uncertainty based on some probability consideration, the boundary between them is not clear-cut. The methods that can be applied in evaluating risk and uncertainty range from subjective characterizations to detailed data-intensive models. According to the P&G risk and uncertainty arise from measurement errors and from the underlying variability of complex natural, social, and economic situations. The generic methods of dealing with risk and uncertainty identified in the P&G include:

1) Collecting more detailed data to reduce measurement error. For example, using two-foot contour mapping rather than 20-foot contour quad sheets for economic and hydraulic studies.
2) Using more refined analytical techniques. For example, a scientifically designed stratified random sample will produce better information about average structure values than would file data of uncertain vintage.
3) Increasing safety factors in design. For example, using three feet of freeboard in the preliminary design of a floodwall designed without precise hydraulic information.
4) Selecting alternatives or components of alternatives[35] with better known performance characteristics. For example, replacement-in-kind costs are more appropriate inputs to depth-percent damage curves than market values that can fluctuate wildly in the aftermath of a flood.
5) Avoiding or reducing irreversible or irretrievable commitments of resources. For example, an appropriate risk strategy, is to preserve flexibility in the face of uncertainty.
6) Using sensitivity analysis and risk analysis methods in the evaluation of the estimated benefits and costs of alternatives. For example, inundation reduction benefits based on high, low and expected values of the flood plain structures could be calculated and displayed.

But it is also important to:

- account for the decision makers' and public's attitudes toward risk;
- explicitly present assumptions used in the analysis and some justification for their use;
- identify all key variables;
- specify risk and uncertainty planning objectives; and,
- use creative display techniques to help analyze risk and uncertainty.

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[35] In the current context, alternatives refers to any situation of choice rather than to alternative plans. In the example cited, there are several alternative methods of estimating structure values. The approach chosen has less uncertainty than the alternative choices.

This chapter introduces some specific techniques that can be used to deal with risk and uncertainty in the ways that the P&G suggest. Additional discussion and details of some techniques can be found in the appendices. First the traditional institutional approach of establishing policies or regulations for dealing with risk and uncertainty is briefly reviewed.

REGULATORY APPROACH TO UNCERTAINTY

Water resource planning involves situations replete with complex systems that are not completely understood and data needs that cannot be met. Planning could be crippled by the resulting uncertainty. A practical solution to this problem has been to decide many such issues by educated (or uneducated) fiat.

The regulatory approach to uncertainty involves situations where values of important variables are either unknown or the subject of considerable uncertainty or debate. The uncertainty is handled by guidance, regulation, or directive that establishes an arbitrary value to be used in the absence of a definitive answer. These are convenient rules of thumb and accepted practices that have, through precedent, come into common use. Note that regulation of uncertainty refers to agency policy. It does not refer to engineering design standards.

The value of such a system is that it resolves the problem and permits the analysis to proceed. The danger in this approach is that it removes the responsibility for assessing a situation from the analyst's shoulders and may foreclose options for decision makers. When unknown values determined by fiat are relatively unimportant the impact of institutionalized uncertainty may be also. In other cases the impact may be significant.

Regulated uncertainty should be scrutinized and improved upon wherever possible, especially where guidance only avoids a dilemma and does not contribute materially to the quality of a decision. This is not a rallying cry to ignore guidance. It is a charge to analysts and decision makers to consider alternative approaches to solving problems other than relying on precedent whose major attribute is that it enjoys acceptance within the agency.

Some examples of regulated uncertainty in the Corps' planning process include: navigation channel width clearance factors; underkeel clearance; assumptions of no increase in share of commodity movements; prescribing forecasts of ten years (hydropower) or twenty years (navigation) when more or less may be appropriate; use of rail rates in place of long run marginal costs; prescribing set freeboard allowances for levees; use of Log-Pearson Type III distributions for hydrologic analysis; restricting affluence factors to 75 percent; assuming participation in the flood insurance program, full employment, constant prices, and risk neutrality; using the federal discount rate as a matter of convenience; reliance on time and money constraints rather than statistical methods to determine sample size; rote acceptance of depth-percent damage relationships; and fifty year project life.

RISK AND UNCERTAINTY ANALYSIS: AN ORGANIZED APPROACH

To handle some risk and uncertainty problems we may need more information. Data uncertainty can result from sampling errors, measurement errors, choice of inappropriate data, extrapolation, or transformation of data. Analysts may have doubts about causality, accuracy of estimates, people's perceptions, effects of events/assumptions, probabilities of events or values being realized, and so on. They may not know what model to use or what parameter values to use for the model.

In other cases, we may be uncertain about goals and objectives. Planners may need clearer priorities or more guidance, decisions, or public involvement. They may be uncertain about what particular effects of alternatives should be compared, time-horizons for effects or planning, trade-offs between long and short term effects, value judgments about weighting the effects and alternatives, and so on.

An operational taxonomy of potential sources of risk and uncertainty in Corps' projects and planning studies can help in identifying risk and uncertainty and selecting appropriate techniques for dealing with it. The taxonomy adopted here is a modified version of a taxonomy developed by Ballew, et al., (1988). Risk and uncertainty of Corps' projects are considered in three dimensions: temporal, spatial/geographic, and social/cultural. The time dimension is divided into the past, present and future. The geographic dimension is scaled from the study area to the national level. The social dimension is separated by major interest group, e.g., the public, local government, state government, agency, and federal government. The division of the dimensions is entirely arbitrary. These examples are suggestive of the ways in which dimensions can be divided. The taxonomy can and should be adapted to fit the needs of the situation.

Within each dimension and its divisions two categories are distinguished: assessment and management, consistent with the dichotomous model described in Chapter 2. Each category is further divided into subcategories. The assessment category includes uncertainties about data, theory, and methods. The management category includes uncertainties about perceptions, values, objectives, institutions, and technology.

Table 5-1 presents a summary display of this taxonomy. Once key variables have been identified this table provides one orderly approach to dealing with the risk and uncertainty inherent in each variable.

The taxonomy offered here can help identify those risk and uncertainty problems that should be addressed. It does not provide answers to the problems: specific techniques are needed to do that. The techniques presented below are divided into those most applicable in the assessment of risk and uncertainty and those most applicable in the management step of the analysis. The division is arbitrary to some extent, in that there is obvious overlap between the technical tasks of estimating values and using those values in the decision process.

RISK AND UNCERTAINTY ASSESSMENT TECHNIQUES

Data

Data problems can be broadly considered to be quantity problems (not enough data) or quality problems (data not reliable or not good enough). The "best" solution is obvious: collect more and better data. These data can be obtained through purchase of data bases, technical investigations, original research, literature searches, surveys, or use of proxy variables. The second best solution is to make the best of the available data. Careful scrutiny and editing of existing data to eliminate or minimize errors and application of appropriate analytical techniques

	Time			Spatial				Social/Cultural			
	Past	Present	Future	Study Area	Region	State	Nation	Public	Non-Federal Partner	State	Corps of Engineers
Assessment											
Data											
▪ not available											
▪ insufficient											
▪ sampling problems											
Theory											
▪ not available											
▪ insufficient											
▪ incorrect											
Methods											
▪ not available											
▪ not well developed											
▪ measurement problems											
Management											
Perceptions											
▪ uninformed											
▪ unknown											
Values											
▪ conflicting											
▪ unknown											
Objectives											
▪ not clear											
▪ conflicting											
▪ unknown											
Technology											
▪ alternative actions											
▪ alternative decision process											

Table 5-1: Taxonomy of Sources of Risk and Uncertainty

in using the data may be the best an analyst can do.

Assumptions

In the absence of determinate information it is often necessary to make assumptions based on judgement and the available data. Assumptions should be based on the best information available and the application of the most appropriate analytical techniques to that data.

The assumptions used in the planning process should be explicitly stated. Each technical appendix, e.g., economics, hydrology and hydraulics, foundations and materials, cost estimates, formulation, etc., should contain an attachment listing all the assumptions used in the analysis. Main reports should list the assumptions that are most critical to project feasibility and formulation. Alternative assumptions considered should also be addressed.

Sensitivity Analyses

EC 1105-2-179 defines *sensitivity analysis* as:

> "...the technique of varying assumptions to examine
> the effects of alternative assumptions on plan

> formulation, evaluation and selection. This can include variation of model parameters as variation of benefit, cost, and safety parameters. One of the important uses of sensitivity analysis is to investigate how different values of certain critical assumptions and parameters could result in changing the choice of the selected project and report recommendations.
>
> Sensitivity analysis is the systematic evaluation of the impacts on project formulation and justification resulting from changes in key assumptions underlying the analysis..."

The guiding principle for risk and uncertainty analysis should be to allocate resources to sensitivity analysis of those factors (models, parameters, variables, issues) that appear to be most important to project formulation and feasibility. Identification of key variables and issues during the planning process is critical for good sensitivity analysis. A range of reasonably likely outcomes can then be described by varying assumptions about engineering, economic, environmental, and social factors and examining the effects of those variations on benefits, costs, safety, and other issues.

Sensitivity analysis can be used to bracket forecasts, parameters, benefit and cost estimates, and other factors for which a range of values can be expected to occur. The sensitivity analysis may be applied at the micro-analytical level, e.g., changing the value of a probability distribution parameter; or at a macro-analytical level by varying *the without project condition*. Evaluating and contrasting extremes can be very useful in defining the relevant range of possible outcomes.

Probability

Classical probability theory is already used in many engineering and economic analyses. Its use should be expanded into all appropriate areas. Recognition of key factors in the planning process as random variables with probability distributions can aid the analyst in identifying relevant analytical techniques for specific problems. Techniques of counting[36], conditional probabilities, discrete and continuous distributions, joint density functions, marginal density functions, and Markov chains are all useful concepts.

Subjective probability analysis is based on the interpretation of probability as a degree of belief fundamentally internal to the individual. Subjective probability expresses the observer's personal uncertainty about events in the world. This is in direct contrast to the classical or frequentist view of probability as a property of the world. When classical probability theory is not possible due to lack of information about the frequency of events, subjective probability analysis can be a useful technique for dealing with risk and uncertainty issues.

Bayesian analysis builds directly on the concept of subjective probabilities. In a world of uncertainty prior beliefs about the likelihood of events occurring or different values of parameters

[36] For example, sampling with and without replacement, permutations and combinations.

obtaining, etc. are inevitable. Prior beliefs allow us to select and formulate models, assess the results of others' work, etc. They may be more convenient than precise but they often provide the only information available. Bayesian techniques use both subjective beliefs (prior distribution) and test or sample data (likelihood function) to develop probabilities (posterior distribution) of events.

For an introduction to objective probability and Bayesian inference see the text by Wonnacott and Wonnacott (1985). Subjective probability is discussed in an accessible way in several articles in the book edited by Gardenfors (1988) and in the article by Poirer (1988) with comments. Also see Appendices C, D, E, and J.

Statistical Techniques

Descriptive and inferential statistics are invaluable tools in risk and uncertainty analysis. Classical statistical methods provide us with measures of central tendency and dispersion that are useful sources of information. It is particularly helpful for analysts to have a sound understanding of the theory of expected values. Hypothesis testing, confidence intervals, analysis of variance, curve-fitting, sampling techniques, correlation, and regression analysis are also useful statistical techniques.

Some test procedures are performed without any information about the distribution of the underlying population. A test that assumes no knowledge of the population distribution is called a nonparametric or distribution-free test. Nonparametric tests are quick and easy to compute and they can be based on qualitative responses such as "failure" and "success". Some of the better known nonparametric tests include the Wilcoxon rank-sum test, sign test, runs test, Spearman rank correlation coefficient, Kruskal-Wallis test, and Kolmogorov-Schmirnoff test.

For an introduction to statistical techniques see the text by Wonnacott and Wonnacott (1985) for classical statistics and Walpole and Myers (1978) for nonparametric statistics. Also see Appendices C, D, and E.

Sampling Techniques

To make inferences about a population based on information contained in a sample, statistically valid sampling techniques are needed. Sample design is one of the easiest and often most overlooked ways of minimizing uncertainty in data for analysis. Sampling techniques focus attention on the size of the sample and the variation to maximize the useful information contained in the sample. Simple random samples are based on the entire population. Stratified random samples separate the population elements into non-overlapping groups called strata. Simple random samples are then collected from each stratum.[37] A cluster sample is a simple random sample in which the sampling unit is a cluster or collection of elements.[38]

For an introduction to sampling techniques see Appendix E and the text by Scheaffer, et al, (1979).

Forecasting

Forecasting is a basic technique for dealing with the uncertainty of describing future events. There are numerous techniques available. Trend extrapolation, regression analysis, and moving averages are but three of them. The IWR Handbook of Forecasting Techniques (IWR Contract Report 75-7) provides an excellent listing and summary description of 73 different forecasting techniques. For an introduction to forecasting see Appendix G.

Simulation

Analytical solutions to problems are generally preferred when they are available. In the context of the model used they tend to remove any ambiguity about the results obtained. Too often in water resources planning the systems under study are too complex to be successfully modeled in a way that results in a clear analytical solution. Where analytical solutions do not exist or when the details of complex systems are poorly understood simulation techniques can be effective.

Computer simulations are well known to many Corps planners. Ship simulators have been used for some time to train pilots and masters and to aid in the design of navigation channels. Physical simulations include models like those used by the Waterways Experiment Station and ship simulators that rely on animation, video tape, and other techniques. Computer simulations can be developed from a variety of simulation languages, commercial programs, or relatively simple mathematical processes like Monte Carlo techniques.

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[37] Faced with the task of conducting a routing study for the inland waterway a sample of movements could be selected from the entire population or the population could be segmented according to origin-destination pairs by river segment and/or by commodity. By selecting from the OD pairs and commodity groups that are most important, it is possible to obtain more information than a simple random sample would yield.

[38] A stage damage survey may define a cluster of homes as one block. The sample would then be based on the random selection of an optimal number of blocks rather than an optimal number of homes. Cost minimization would justify the use of this technique.

For an introduction to simulation techniques see Appendix H and the text by Sang Lee (1988).

Mathematical Programming

Determining the values of certain variables subject to a set of constraints so as to maximize (or minimize) a given function is a mathematical programming problem.[39] Mathematical programming techniques can be useful in dealing with certain risk and uncertainty problems alone or in combination with other techniques.

Classical programming involves choosing values of certain variables so as to maximize or minimize a given function subject to a set of equality constraints. Nonlinear programming involves choosing nonnegative values of certain variables to optimize a function subject to a set of inequality constraints. Either the objective function or the constraints contain non-linear relationships. Linear programming involves choosing nonnegative values of certain variables so as to optimize a given linear function subject to a set of linear constraints.

Integer programming is a special programming case in which the answer is required to consist of integers. Such problems are not infrequent in economics where many items come in indivisible units. Dynamic programming involves choosing the values of certain control variables over a period of time (also called choosing the time path of variables) so as to result in a corresponding time path for certain state variables that describe the system in a way that optimizes the value of a given function over time subject to a set of constraints.

For an introduction to these programming techniques see the texts by Lial (1979), and Intrilligator (1971).

Econometrics

Econometrics is a combination of economic theory, mathematical economics, and statistics. It is distinct from any one of these three branches of science, yet derives its strength from the unification of all three. The purpose of econometrics is to provide numerical values for the parameters of economic relationships and to verify economic or other causal theories.

Econometrics assumes that relationships are not exact. Econometric methods are designed to take into account the random component characteristic of economic relationships that create deviations from exact behavioral patterns suggested by theory and mathematical models. These methods can often be adjusted for the measurement of stochastic relationships and applied to theory outside the realm of economics. Though econometrics is more than regression analysis it is frequently identified with that statistical technique. For an accessible introduction to econometrics see the texts by Koutsoyiannis (1985) and Wonnacott (1978).

[39] Reservoir system operating studies were among the first to apply mathematical programming techniques in the water resource field. IWR is currently sponsoring research to apply mathematical programming techniques to the analysis of environmental mitigation.

Expert Opinion

When data are scarce, the best information may the experiential or subjective opinions of experts in that particular area of uncertainty. Expert opinion is inherently biased. It is based on the beliefs and experiences of a single person. To guard against this bias the opinions of many experts should be sought. It is also helpful to understand the nature of each expert's experience in weighing the impact of an opinion.

A variety of techniques have been developed to elicit opinions, estimates, recommendations, or decisions from a group of experts. Specific techniques include eliciting subjective probabilities, aggregating opinions, and consensus building techniques such as the Delphi method. Consensus building or decision making techniques can be useful in developing alternative scenarios and forecasts. These techniques are appropriate in areas of considerable scientific uncertainty or disagreement. They are not appropriate when more objective and analytical techniques can be used except to the extent they provide additional information.

Financial Risk

Capital budgeting problems involve analysis of trade-offs between risk and return on investment (ROI). Riskier projects often promise greater returns. The cost of capital is a function of the level of risk of the firm. Firms typically add a risk premium to the cost of capital that is proportional to the coefficient of variation for the return on investment. They use a risk-adjusted discount rate. This technique is called a risk-return trade-off analysis. For an introduction to this technique see the text by Keating and Wilson (1987).

As projects become riskier the existence of the firm does likewise. It has been argued that the federal government is not analogous to a firm in this respect. The government has risk pooling and risk spreading options that a firm does not have. With a need to "do business" with a non-federal partner, this argument may not be as compelling as it once was. Risky projects imply a risk that the Corps could lack a pool of willing partners for its projects.

While current policy obviates the need for the Corps to address the ROI issue, the potential for increased private sector involvement in water resources planning and development may well lead the Corps into this area.

Option Value

It has been suggested (Weisbrod, 1964) that when future demand for a public good is uncertain there may be value in retaining the option of consuming that good, apart from consumer's surplus. Several values have been suggested as the correct measure of the value of this willingness to pay for this option: two of these are options value and option price. Option value represents the risk premium a risk averse individual would be willing to pay that is in excess of the expected value of the consumer surplus for the option of consuming that good. Option price is the difference between willingness to pay for the option of consuming a resource in the future and expected consumer surplus from that consumption. Option value can be a positive or negative value.

The implication of this for water projects is that the opportunity cost of a resource that could be irretrievably lost may include this option value. For an introduction to option value see Appendix F and the text by Fisher (1983).

Risk-Cost-Benefit Tradeoff

There are at least two variations of the risk-cost-benefit tradeoff. First, if there are alternative ways to provide the desired benefits and each alternative has an acceptable cost, then choose the alternative with the least risk.[40] This approach simply minimizes risk subject to the constraint of providing the basic benefits at an acceptable cost.

In the second approach, resources can be applied to a project for the purpose of further reductions in risk to the point where the marginal cost of reducing the risk just equals the value of the marginal reduction in risk. When this type of optimal design is obtained the residual risk may be defined as the acceptable level of risk in the sense that it would be economically inefficient to pursue further reductions in risk. This argument is most effective when risks and costs of reducing them can be reasonably categorized in dollar terms.

RISK AND UNCERTAINTY MANAGEMENT TECHNIQUES

Decision Rules

Decision rules can be developed to aid the decision process. The Corps already applies the net benefits and benefit-cost ratio rules to its project evaluation. Other rules in use include cost minimization, maximum safety, and minimum sum of construction costs and residual risks. Rules for decision making under uncertainty have been developed and include the Laplace, maximin, dominance, Hurwicz, and minimax criteria. For an introduction to these criteria see Appendix I.

Decision Trees

Many decisions are the result of a complex series of sequential decisions required to reach a "best" decision. A decision tree is a schematic tool for evaluation of sequential decision problems.

Decision trees consist of:

1) Decision points: Specific points of time when a decision must be made are shown as decision points.
2) Event points: A number of states of nature that may occur are shown as event points.
3) Probabilities: The known or subjective probabilities of events are presented above each of the event branches.

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[40] In the case of Corps' projects acceptable cost could be interpreted as "each alternative is economically justified." Alternatively, costs can be subsumed under benefits as negative benefits and positive net benefits imply acceptable costs.

4) Conditional payoffs: The conditional payoff of each event branch is estimated and recorded at the end of each branch.

Figure 5-1 shows the structure of a typical decision tree. A decision tree starts with one or more initial decisions and branches to all possible and feasible decision alternatives that follow it. At the end of each alternative an event or decision point is added. The corresponding probability of each event is recorded. Branching continues until conditional payoffs are recorded. Each decision branch (i.e., each possible path created during development of the tree) is evaluated by computing its expected value.

Heuristics

Faced with uncertainty most people revert to the use of certain rules of thumb that have proven useful to them in similar situations in the past. Cognitive psychology research suggests subjects make judgments on such inferential rules or heuristics. Though heuristics are frequently used means for dealing with uncertainty they are not always valid and can lead to large and persistent biases in decision making. Heuristics, though sometimes useful, can be particularly invidious because they are often unknowingly practiced by "experts." Tversky and Kahneman (1974) offer the following heuristics as sources of bias in judgments:

1) Anchoring and adjustment. Individuals tend to produce estimates by starting with an initial value and adjusting it to obtain a final answer. The adjustment is typically insufficient. As a result, initial ideas play too large a role in determining final assessments. Experts are prone to use this rule. When faced with uncertainty they make an initial guess and adjust it up or down but they rarely venture too far from their first guess or anchor.

2) Availability. If it is easy to recall instances of an event's occurrence, that event will tend to be assigned a higher probability than it deserves. People tend to overestimate the probabilities of dramatic events that have recently occurred. This rule may help to explain the often observed fixation with protecting against a recent low probability flood of record.

3) Coherence and conjunctive distortions. A good story makes events seem more likely. The probability that a sequence of events will occur often seems higher than it should, especially when the events fit a plausible scenario. The scenario of events required to produce a dam failure may seem to be far more likely than it in fact is.

4) Representativeness. People expect that the essential characteristics of a stochastic process will be represented in any part of the process. Furthermore, people see chance as a self-correcting process in which a deviation from the mean in one direction is offset by a deviation from the mean in another direction. Experts and laymen alike may make too much of a few years of data in trying to understand complex processes.

5) Overconfidence. People, particularly so-called experts, generally ascribe too much confidence to their estimates, thereby underestimating confidence intervals. This rule motivates people to see patterns where none exist, to reinterpret data to be more

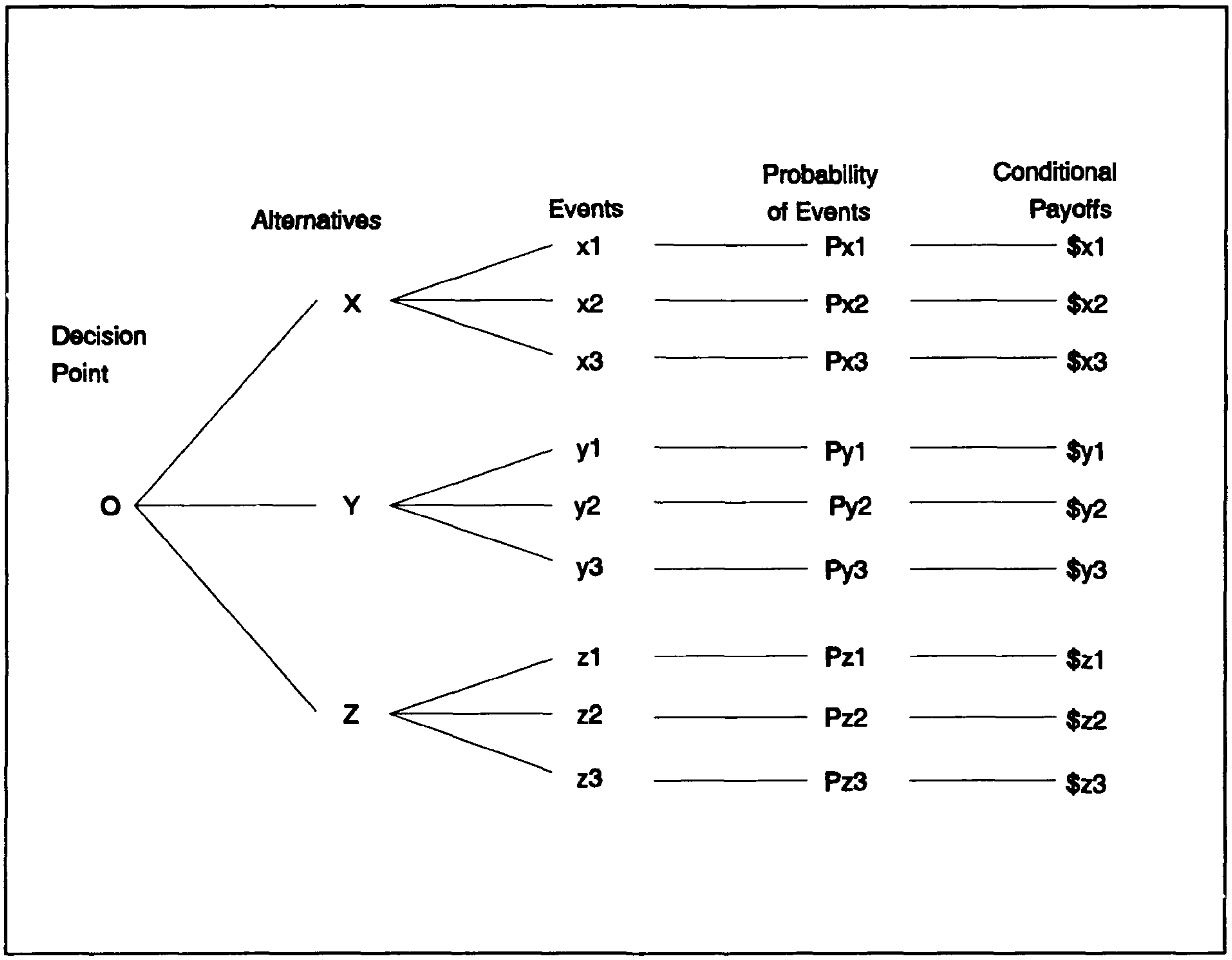

Figure 5-1: Structure of Decision Tree

consistent with their view, and to ignore evidence that contradicts their position.

Incremental Strategy

Incremental strategy was first applied to inventory problems. In that context the inventory decision was evaluated one unit at a time. The expected loss from not stocking the first unit and losing a sale is compared to the expected loss of stocking the first unit and not selling it quickly.

Using the incremental strategy planners develop options for the short term that allow them to maintain flexibility in the planning process. Phased construction is the most familiar example of this kind of planning.

Strategic Choice Approach

Planning is a process of making interrelated decisions over a period of time under conditions of uncertainty and changing circumstances. The strategic choice approach is a type of planning that has developed a number of ways to learn more about uncertainty in decision making. One such way is to convert uncertainty into risk where possible. "Surprise limits analysis" can be used to approximate the outer bounds of one's estimate of the risk entailed in the decision.[41] Sensitivity analysis can be used effectively to identify the most important sources of uncertainty that can be reduced.

Another approach is to use pairwise comparisons of the alternatives, noting the uncertainty in each. These and other approaches are described in more detail in the work of Ballew et al (1988).

Multiobjective, Multiattribute Utility Theory and Goal Programming

Decision problems under risk and uncertainty rarely involve a single objective. Water resource planning requires that multiple objectives be addressed. An alternative plan is evaluated based on its contributions to a number of planning objectives. Alternative plans will likely yield varying contributions to meeting the planning objectives.

If the contributions of an alternative to the different planning objectives can somehow be added up, the problem of multiobjective or multiattribute decision making can be reduced to a single objective decision. The most common approach is to specify the alternatives' contributions to planning objectives in an ordinal or preferably cardinal measure that can be weighted and/or summed in an order-preserving way.[42] Utility is often the common denominator that is used to quantify contributions to multiple objectives. The difficulty with this process is in specifying the utility function and in distorting complex realities in order to simplify the problem.

Several software packages including MATS and Electre have been developed to provide an analytical framework for multiobjective or multiattribute decision making.

Goal programming, first developed as an extension of linear programming, can be applied to various decision problems having a single objective and multiple subobjectives as well as to problems with multiple conflicting objectives and subobjectives. The goal programming model attempts to obtain satisfactory levels of objective attainment that would be the best possible solution given the decision makers' view of the relative importance of the various objectives. This technique requires a weighting system for the objectives so that the less important objectives are not pursued until the more important ones have been achieved to a satisfactory level. All objectives are subject to the constraints of the problem. The weighting scheme converts all objective attainment into a universal criteria such as a number of points or utilities.

Goal programming is a relatively new technique that has the same basic limitations, assumptions, requirements and solution methods as linear programming. For an introduction to goal programming see the text by Lee (1972) and articles by Charnes (1961) and Ijiri (1965).

[41] Respondents are asked a series of questions to elicit the limits of their uncertainty. The technique might be applied to elicit subjective probabilities about failure of a wicket in a dam, for example. Here the respondents would be asked, would you be surprised if a wicket failed in the next six months? In the next year? Correspondingly, one might ask, would you be surprised if five years passed with no wicket failure? Ten years?

[42] For example, see Yacov Haimes' (1985) treatment of the partitioned multiobjective risk method.

Expected Utility Theory

Experience demonstrates that people do not always make decisions based on maximizing the expected value of an outcome. Insurance industries operate on the knowledge that in many situations people are risk averse and are willing to pay a risk premium in addition to the expected value of their loss to avoid future losses. In a flood control context risk averse behavior implies that people may be willing to pay more than their expected annual damages to avoid flood damages. Thus, expected annual damages may, conceptually, be a lower limit on the benefits of flood control to risk averse people.

Experience and research in a variety of fields have lead to the use of expected utility theory for decision making under uncertainty. The significance of this theory is that in uncertain situations people act as if they are maximizing expected utility rather than expected values. Von Neumann and Morgenstern (1953) were the first to construct a set of axioms defining expected utility - maximizing behavior.

The advantage of this decision making theory is that it often describes choices people actually make better than does expected value maximization. It is also a technique decision makers can adopt. Its greatest disadvantage is that it requires specification of a utility function. For an introduction to this theory see Appendix F.

Survey

Questionnaires, opinion surveys, and focus groups are some options developed to high art forms by the American political process that are available to the decision maker for reducing the uncertainty surrounding a decision. Surveys can be conducted face-to-face, by telephone interview, and by mail. The public, local officials, agency personnel, technical experts, or other groups can be the target of the survey. Information obtained from surveys can reduce the uncertainty attendant to many implementation issues, e.g., acceptable levels of residual risk, attitudes about risk transfers, etc.

Expressing Degree of Belief

Subjective probability analysis as described above is based on the interpretation of probability as a degree of belief fundamentally internal to the individual. Subjective probability expresses the observer's personal uncertainty about events in the world. Uncertainty can sometimes be reduced by building a consensus of opinion among experts or decision makers.

Degrees of belief can be elicited in a variety of ways. Direct methods ask respondents to specify numbers. They vary from asking for a single probability estimate or a few numbers to asking for a complete probability distribution function. Optimistic, best, and pessimistic estimates are often requested. Probability estimates are often sought through the specification of odds on events occurring.

Indirect methods of eliciting degrees of belief include:

1) complete pairwise comparisons,
2) incomplete pairwise comparisons,

3) rank ordering, and
4) bisection.

Pairwise comparisons involve consideration of all (complete) or a subset (incomplete) of alternatives, two at a time. When one alternative action dominates all others it is the best course of action. A single best option is rarely obtained by this method due to transitivities. In rank ordering, events or outcomes are ranked by probability of occurrence from most probable to least probable. Bisection requires the respondent to identify a third event that is equidistant in probability from two distinct events specified by the analyst.

Formulation of Clearer Goals, Aims, Objectives, and Policy Guidelines

Uncertainty about what to do or how to do it can sometimes result from unclear goals. Uncertainty about goals, aims or objectives can leave decision makers in the dark about the best decision. The decision process should assure that the goals, aims, and objectives of the study are certain, even if the means of achieving them cannot be.

Policy guidelines may be missing, poorly defined, ambiguously written, or interpreted on an ad hoc basis. Such uncertain policy makes it difficult to formulate clear alternatives. In these cases clarification of the relevant policy in a timely manner can reduce uncertainty considerably in the management stage of the analysis.

CHAPTER 6

RISK COMMUNICATION AND DISPLAY

INTRODUCTION

A well-documented and rational risk and uncertainty analysis is a necessary condition for effective risk communication. Risk communication can be internal or external. Internal communication takes place among analysts and decision makers responsible for the ultimate selection of a project. External communication, the focus of this chapter, is primarily between the Corps and the public.

Analysts, whose messages can be quite technical, need to communicate uncertainty to each other. When analysts communicate to decision makers, they need to be more sensitive to the role of risk and uncertainty in determining project feasibility and selection. For decision makers, the emphasis is on communicating the results of the planning process.

The public must be consulted from the very outset of a study. The information they provide, however, must be frequently reinterpreted to be useful. This can make effective communication a very delicate process. The public may have had first-hand experience with the problem, and using some common heuristics for thinking about chance situations, they may have an unshakably firm belief in their personal understanding of the situation. The difficulty arises when these beliefs are mistaken.

As a result, one early risk communication task facing many study teams is public education. Another task is communicating the likely consequences of a selected project. These tasks are important parts of both the public involvement program and the selection process.

DISPLAY OF RISK AND UNCERTAINTY ANALYSIS

Display of the results of a risk and uncertainty analysis refers to the presentation of the analysis in the project documents. The goal is to communicate both the risk and uncertainty assessment and management processes. A technical appendix summarizing the risk and uncertainty analysis is not desirable for this purpose. Risk and uncertainty analysis is not something to be added on at the end of a study or something to be undertaken to satisfy reporting requirements. It is a tool to be used by planners and decision makers throughout the process to improve the quality of decisions being made.

All study participants should participate in the risk and uncertainty analysis in their areas of expertise and responsibility. Consequently, the risk and uncertainty analysis should be incorporated throughout all tasks in the planning process and reported along with other relevant information describing those tasks. Details should be included in the relevant technical appendices and the most significant issues should be addressed in the main report.

An overview of the cumulative aspects of risk and uncertainty should be addressed in the plan formulation description. The plan selection discussion should explicitly address the resolution of the major risk and uncertainty issues.

The methods used in the report will vary from situation to situation. A clear and concise narrative description of the issues and the options for dealing with them is always appropriate. Innovation in the display of complex information and trade-off analysis is encouraged precisely because of the existing lack of proven, effective techniques.

COMMUNICATION[43]

Internal Communication

Water resource planning is overflowing with uncertain and risky situations. Most uncertain aspects turn out to make little difference in plan selection. Generally, a few elements of uncertainty emerge as central to the decision process. These dominant aspects of risk and uncertainty must be identified and effectively communicated to decision makers and the general public, as appropriate.

The primary internal communication task for the analyst is to describe the approach taken in the risk and uncertainty analysis. This is distinctly different from reporting the results or significance of the risk and uncertainty analysis.

Effectively communicating the relevant uncertainty in a project is important to improve the quality of decision making and to avoid the inefficient allocation of resources. The importance of effectively dealing with uncertainty can hardly be overstated. Communicating the relevant risks of a project takes on an extra dimension of importance when there are potential effects on the life, health, and safety of the community. At this point the issues transcend resource allocation issues and cross over into the very real world of public opinion where emotion and value judgments often weigh more heavily than an objective risk and uncertainty analysis.

External Communication

The external risk communication can be structured according to who is responsible for making the decision, the risk communication objectives, and the possible strategies available for implementing them. Communicating risks to the public is itself a decision problem fraught with complexities. Following the model developed by Keeney and von Winterfeldt (1986) some complexities of risk communication are reviewed, followed by discussion of possible risk communication objectives and strategies for obtaining them.

Complexities of Risk Communication Problems

The complexities of the risky phenomena, i.e., the floods, storms, dam failures, collisions, residual risks, etc. lead to complex objectives and thus complex alternatives for achieving such objectives. The public prefers simple issues and simple terms, like safe or unsafe. Such simplification is not always possible. The entire spectrum of risks, objectives, and alternatives

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[43] The following sections present an overview of aspects of risk communication. A fuller treatment of the problems and issues are presented in the IWR report "Guidebook for Risk Perception and Communication in Water Resources Planning" (Draft Report), December 1991.

must be considered by the decision makers. Such complexity cannot be relayed to the public in simple terms.

The risks may involve threats to life, health, and safety; environmental damage; socioeconomic effects; political implications; and engineering performance of structures. The complex interdisciplinary nature of the problems and the expanse of knowledge necessary to understand them complicates communication.

Risk communication is made all the more difficult by the uncertainty inherent in the scientific evaluation of the available data. The public tends to count on the opinions of "all-knowing" experts. Communication is difficult when the experts are not only not "all-knowing" but they don't even agree among themselves.

One particularly serious problem in the interaction between agency personnel and the public is the difference in the way they structure and perceive risk problems. The agency typically has some legislation or policy guidelines directing them in their objective approaches to problems and their resolution. The Corps has an extensive legislative history and finely developed policy guidelines.

The Corps' responsibility to consider National Economic Development provides a prime example of how the agency position differs from the public's formulation of the same problem. Balancing benefits, costs, residual damages, etc. is apart of the Corps' problem formulation, but to the public these aspects of the problem are bureaucratic esoterica. The public, on the other hand, is generally less concerned about national objectives and values but more concerned with a projects personal and community impacts.

The language chosen for communicating risks can present a substantial barrier to communication. Phrases such as expected annual damages, statistical collisions, probabilities of failure, and statistical lives lost are a language foreign to most people. It is appropriate that analysts communicate with each other and with decision makers in such technical language. But when the time comes to talk to the public, it is critically important to use nontechnical terms that the public will understand.

The risk and uncertainty analysis will likely stress those aspects of the problem that are quantifiable. The public, meanwhile, is moved more by the qualitative aspects of a problem. For example, they will think of those things they fear or dread. The analyst will discount rare catastrophic events with small probabilities of occurrence (e.g., a dam failure), while the public may dwell on them because of their drama. Effective risk communication must address such human tendencies.

During the planning process, significant risks to the community will have been identified. Identified alternatives will necessarily embody some residual risk. The public generally prefers zero risk and complete certainty to any of the project alternatives. One of the most important points to be made at this time is that a risk-free environment is not one of the options available to the public. The options lie along a continuum from more to less risky (and often, correspondingly, from less to more costly).

The public's desire for certainty is most obvious in their lack of patience or understanding of cautious expressions of scientific knowledge. Uncertain expressions of risks are particularly vexing to the public. These characteristics of the public make responsible communication of risk information more difficult.

The major issue from the public perspective is often the extent to which the risk has been reduced to an acceptable level. Unfortunately, this requires a clear definition of goals and what is deemed an acceptable risk. These will rarely exist. Thus, applying this criteria is more like making a judgment and then seeing if the judgment does or can achieve a consensus.

Evaluating the acceptability of residual risks or new risks created by a project is best done in a with and without project condition context. A clear description of existing risks without a project, both currently and in the future, provides an effective context from which to initiate communication about acceptable levels of risk. Emphasis can be placed on risk reductions or residual risks, as appropriate.

General mistrust of the government can result in a decrease in credibility or suspicion of a hidden agenda, often the belief that a decision has been made long before the public is consulted. Such an atmosphere can poison any communication. Risk communication is hurt all the more because of the above complexities it may also face. An atmosphere of mistrust can be avoided by an open planning process with a vital public involvement program.

Objectives and Strategies for Public Risk Communication

Keeney and von Winterfeldt (1986), in an excellent summary, identify six possible objectives of public risk communication. Included are:

1) To better educate the public about risks, risk assessment and risk management;
2) To better inform the public about specific risks and actions taken to alleviate them;
3) To encourage personal risk reduction measures;
4) To improve the understanding of public values and concerns;
5) To increase mutual trust and credibility; and
6) To resolve conflicts and controversy.

Although these objectives embody the spirit of building a consensus among the public on the correctness of a decision, it should be bore in mind that persuasion is always one objective of the risk communication.

To better educate the public. Part of the risk communication task is to improve the public's ability to handle risk information and interpret risks. There are three areas in which general public information about risks can be improved:

1) To put risks in perspective;
2) To understand the complexities of risk problems; and
3) To understand the rationale of risk assessment and risk management.

It seems a worthwhile goal to increase public awareness of the extent and magnitude of risks, for the purpose of improving public decisions.

Educating people about the enormous complexities of risks can improve understanding of the difficulties encountered in risk assessment and management. In particular, the public should know that:

1) There are no zero-risk solutions;
2) Tradeoffs are necessary; and
3) Uncertainty cannot be avoided.

These are lessons that are best taught early and often in the planning process.

To better inform the public. The immediate goal of the communicator is less to educate people than to inform them about specific risks, their assessment, and options for managing them. Some means to achieve this objective include:

1) Improving the presentation of risks and analyses by avoiding technical and bureaucratic language;
2) Casting the results of risk analyses in terms that make sense to laymen and that allow them to learn and gain experience with the information; and
3) Improving the interaction by using information transmitters, like science writers, community leaders, and members of the media.

As an example, telling the public there is a 10^{-7} chance of a dam failure in any year provides them with inadequate useful information about the risk. They are likely to respond by asking, "But is it safe to live downstream of the dam?" Thus, a first strategy is to find out what people care about, and cast the results of risk analysis in those terms.

Information that people can understand, relate to personal experience, and learn can produce more effective communication. Information should be presented in as receptive an environment as possible. Try to avoid presenting risk information in a crisis situation or one involving political controversy whenever possible. The solution is not to withhold information but to provide it as soon as practical, in as receptive a setting as can be managed.

To encourage personal risk reduction measures. Encouraging people to take steps to reduce risk to themselves and others seems to be a worthwhile objective. Some simple and relatively inexpensive actions for reducing individual risks are available. Flood insurance, nonstructural measures applicable to individual homes, and flood warnings and evacuation plans are some examples. Unfortunately, the strategies for achieving this objective are far from clear.

Research has shown that negative advertising campaigns have limited success in changing personal behavior. Pictures of flood damages will do little to increase participation in flood insurance programs. Nonetheless, creative application of lessons learned from the advertising and public relations fields may be very useful in motivating people to act in their own best interests.

To improve the understanding of public values and concerns. Effective risk communication is a two-way street. To address the concerns of the public, regulators must understand their concerns and fears. An understanding of these concerns and fears will also help planners to formulate more relevant criteria to address tradeoffs in risk management.

Analysts are experts in the technical aspects of risk assessment and management. No one is an expert in the value side of risk issues. Value tradeoffs require input from many groups. Obtaining these inputs from public groups is still an art that will rely heavily on lessons learned from public involvement programs.

To increase mutual trust and credibility. An agency's credibility is its most important asset when communicating with the public. This is all the more true with risk communication. The best tactic is to guard and ensure the agency's credibility. This is best done by being completely honest. State your true communication objectives explicitly. If the objective is to persuade people, state it so, then communicate in a straightforward manner. Do not evade questions or the full truth. Never hide behind bureaucratic arguments or references to regulations and guidelines as reasons for doing or not doing something. If a regulation prescribes something use the rationale for the regulation as the reason rather than the regulation itself. Do not second-guess your audience.

To resolve conflicts and controversies. Risk problems and tradeoffs can become the subject of heated debate and prolonged controversy because they affect people directly. There are a variety of methods available for dealing with and resolving conflicts. Early involvement of all stakeholder groups is an element of each of them. Successful risk communication requires learning the values and concerns of these groups and taking them seriously.

CHAPTER 7

A RISK AND UNCERTAINTY ANALYSIS OUTLINE

INTRODUCTION

There is no formula for conducting a risk and uncertainty analysis. There are no set procedural steps to follow. There isn't even a menu of issues, analytical procedures or decision making algorithms from which an analyst or decision maker can confidently choose. Each risk and uncertainty analysis is as unique as the problems presented, alternatives possible, and people involved.

In an effort to provide some guidance for beginning the process of integrating risk and uncertainty analysis into the Corps' planning, an outline is provided in this chapter. The outline is not a prescription for risk and uncertainty analysis. It is merely a compilation of some generic, and often simply common sense, thoughts about how one might begin to think about incorporating risk and uncertainty analysis into the plan formulation process. As such it is to be considered as a perfectly viable starting point for Corps planners.

OUTLINE

The following work plan provides a generic approach to the identification, assessment, and display of risk and uncertainty in a typical Corps' project. The focus of this work plan is on early planning to ensure effective use of project planning budgets and efforts. Special attention must be directed towards tracking key issues through the six planning steps, addressing the cumulative and synergistic effects of risk and uncertainty, and displaying the results of the analysis for decision makers.

I. Preparation

A. Preview the Study Area.

1. Overview of major economic, social, and political activities and actors in the area and affecting the region.
2. Identify key interest groups, opportunities, and problems, paying particular attention to those that may create issues of conflict during the planning process and project implementation.

B. Plan Effort to Identify Key Risk and Uncertainty Issues.

1. Review "typical" project issues and list potential issues with respect to the six planning steps.
2. Develop a taxonomy of sources of risk and uncertainty (i.e., see Table 5-1).
3. Identify potential key variables and other risk and uncertainty issues.

C. Develop Risk and Uncertainty Objectives.

1. Preliminary identification of all significant risk and uncertainty issues.
2. Evaluate the individual and cumulative effects of risk and uncertainty.
3. Plan to track risk and uncertainty issues through the six step planning process to provide improved information to decision makers.
4. Preliminary judgment of the effects of risk and uncertainty on project benefits and costs, and on alternative project BCRs.
5. Preliminary identification of acceptable risks, residual risks, and project-imposed and/or transferred risks.

D. Plan Project Data Collection and Assessment Efforts.

1. Identify assessment methods for preliminary key risk and uncertainty issues.
2. Evaluate data requirements related to assessment of key risk and uncertainty issues and plan data collection efforts.
3. Review budgets with respect to significant risk and uncertainty-related data collection and assessment needs.

E. Plan Display and Communication of Risk and Uncertainty Issues and Effects.

1. Review methods of displaying and communicating results of risk and uncertainty analysis to decision makers.

   a. Track the important issues through the six planning steps.
   b. Illustrate the effects on project BCRs.

2. Evaluate needs of the public with respect to risk and uncertainty issues: develop public involvement, education, and communication strategies.

II. Risk and Uncertainty Identification

A. Identify and list all assumptions, models, parameters, and professional judgements related to problem identification, forecasts of future conditions, and formulation and evaluation of alternative plans.
B. Rank items in identified list to identify potential key variables that can change forecasts, alternative plans, benefits and costs, and project performance.
C. Identify to the fullest extent possible public attitudes toward acceptable residual risks, risk-cost trade-offs, risk transfers, and project-imposed risks.
D. Develop a system for tracking risk and uncertainty issues through the planning process, so as not to lose sight of their impacts in each planning step.

III. Risk and Uncertainty Assessment

A. Plan assessment strategy, and select appropriate methods for dealing with key variables and other important issues.
B. Collect data needed for planning and risk and uncertainty assessment.
C. Assess risk and uncertainty.

1. Apply appropriate statistical or quantitative methods wherever possible, or provide a detailed description of the issues if more rigorous methods are unavailable.
2. Utilize sensitivity analysis to examine the effects of changes in key variables on forecasts; alternative plan formulation; benefits, costs, and BCRs of alternative plans; and other measures of project performance.
3. Identify conditions under which feasibility of alternative plans erodes.

   a. When the BCR falls below 1.
   b. When the plan is no longer acceptable for other reasons.

D. Determine levels of residual, imposed, and transferred risks associated with alternative plans.

E. Determine overall, cumulative levels of risk and uncertainty for each alternative plan; i.e., what is the probability that a project will not perform as expected, or that an expected BCR will not be realized, given the likelihood of the scenarios on which plan formulation was based?

IV. Risk and Uncertainty Management

A. Identify key risk and uncertainty issues and the results of the analysis for the decision maker.

1. List and track all key variables and describe their impacts on the planning effort and its results.
2. Summarize all methods used to handle key variables and other issues in the risk and uncertainty assessment.
3. Highlight how changes in key variables can affect project performance, particularly the BCR.
4. Present forecasts, with project conditions, benefits, costs, and BCRs as mean values with calculated distributions, or as a range of values, instead of as single numbers.

B. Label the important risk management issues that the decision maker must address.

1. Highlight the overall, cumulative risk and uncertainty associated with the recommended and alternative plans.
2. Compare the residual, imposed, and transferred risks of each alternative with the risk and uncertainty attitudes of the public.
3. Identify risk and uncertainty issues that have not been addressed in the risk and uncertainty analysis, or areas where substantial risks and uncertainties still exist.

This outline suggests an approach for integrating risk and uncertainty analysis into the planning process. It is expected that Corps' planners and analysts will modify and improve this outline to fit the unique requirements of specific projects, while following its intent of producing a greater quantity and quality of information for improved planning and decision making.

APPENDICES

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Ballew, M., S. Davis and S. Ratick. "Guidelines for Managing Uncertainty in the Calculation of Flood Damage Reduction Benefits." U.S. Army Corps of Engineers, Institute for Water Resources, 1989.

Bar-Hillel M. "The Base Rate Fallacy in Probability Judgments." Acta Psychologica, 44 (1980), pp. 211-233.

Bawa, V. J. "Stochastic Dominance: A Research Bibliography." Management Science, 28 (1982), pp. 698-712.

Beyth-Marom, et al. An Elementary Approach to Thinking Under Uncertainty, London: Lawrence Erlbaum, 1985.

Borch, K. and J. Mossin eds. Risk and Uncertainty, Proceedings of a Conference of the International Economic Association, Stockton Press, 1968.

Brown, R. and J. Ulvila. "Communicating Uncertainty for Regulatory Decisions," Uncertainty in Risk Assessment, Risk Management, and Decision Making, ed. V. T. Covello et al., 1987.

Cairncross, Sir A. "Academics and Policy Makers," Changing Perceptions of Economic Policy, ed. by Frances Cairncross, 1981.

Charnes, A. and W. Cooper. Management Models and Industrial Applications of Linear Programming, New York: John Wiley & Sons, 1961.

Commission of the European Community. Risk Assessment for Hazardous Installations, Pergamon Press, New York, 1986.

Covello, V. T. et al, eds. The Analysis of Actual Versus Perceived Risks, New York: Plenum Press, 1983.

Covello, V. T. et al, eds. Risk Evaluation and Management, New York: Plenum Press, 1986.

Covello, V. T. et al, eds. Uncertainty in Risk Assessment, Risk Management, and Decision Making, New York: Plenum Press, 1987.

Derman, C., L. Glaser and I. Olkin. A Guide to Probability Theory and Application. New York: Holt, Rinehart and Winston Inc., 1973.

Doherty. Corporate Risk Management, A Financial Exposition. New York: McGraw-Hill, 1985.

Douglas, J., R. Wyzga and P. Ricci. "Toward Better Methods of Risk Assessment," EPRI Journal, March 1982.

Eisel, L. "Uncertainty: The Water Resources Decision Making Dilemma," Risk/Benefit Analysis in Water Resources Planning and Management, ed. by Y. Haimes, 1981.

Fisher, A. Resource and Environmental Economics, Cambridge: Cambridge University Press, 1983.

Gardenfors, P. and N. Sahlin, eds. Decision, Probability and Utility, New York: Cambridge University Press, 1988.

Goicoecha, A., M. Krouse and L. Antle. "An Approach to Risk and Uncertainty in Benefit-Cost Analysis of Water Resources Projects," Water Resources Research, Vol. 18 No. 4 (1982), pp. 791-799.

Graham, J., H. Raiffa and J. Vaupel. "Science and Analysis, Roles in Risk and Decision Making," Risk Evaluation and Management, ed. by V. T. Covello, et al., 1986.

Gratt, L. B. "Risk Analysis or Risk Assessment: A Proposal for Consistent Definitions," Uncertainty in Risk Assessment, Risk Management, and Decision Making, ed. by V. T. Covello et al., 1987.

Greeley-Polhemus Group Inc. Economic and Environmental Considerations for Incremental Cost Analysis in Environmental Mitigation Planning, A Report Prepared for the US Army Corps of Engineers, Institute for Water Resources, February 15, 1990.

Hadden, S. G. Risk Analysis, Institutions, and Public Policy, Port Washington, NY: Associated Faculty Press, 1984.

Haimes, Y. V. "Risk and Impact Analysis in a Multiobjective Framework," Risk Based Decision Making in Water Resources, ed. by Y. V. Haimes and E. Stakhiv, 1986.

Haimes, Y. V., ed. Risk/Benefit Analysis in Water Resources Planning and Management, New York: Plenum Press, 1981.

Haimes, Y. V. and E. Stakhiv, eds. Risk Based Decision Making in Water Resources, New York: ASCE, 1986.

Haimes, Y. V. and E. Stakhiv, eds. Risk Analysis and Management of Natural and Man-Made Hazards, New York: ASCE, 1989.

Henderson, J. and R. Quandt. Microeconomic Theory, A Mathematical Approach, 3rd Ed.,New York: McGraw-Hill Book Company, 1980.

Henley, E. and J. Henley. Reliability Engineering and Risk Assessment, Englewood Cliffs: Prentice-Hall Inc., 1981.

Hey, J. D. Uncertainty in Microeconomics, New York: New York University Press, 1979.

Hurwicz, Leonid. Optimality Criteria for Decision Making Under Ignorance, Cowles Commission Discussion Paper, Statistics, No. 370, 1951.

Ijiri, Y. Management Goals and Accounting for Control, Chicago: Rand-McNally, 1965.

Intrilligator, M. Mathematical Optimization and Economic Theory, Englewood Cliffs: Prentice-Hall Inc., 1971.

Kates, R. W. Risk Assessment of Environmental Hazard, Scope 8, John Wiley and Sons, New York, 1981.

Keeney, R. L. and D. von Winterfeldt. "Improving Risk Communication," Risk Analysis, Vol. 6, No. 4, 1986.

Keating, B. and J. H. Wilson. Fundamentals of Managerial Economics, New York: Harcourt Brace Jovanovich, 1987.

Knight, F. H. Risk, Uncertainty, and Profit, University of Chicago Press, Phoenix Books, 1971; originally published in 1921.

Koutsoyiannis, A. Theory of Econometrics, 2nd Ed., Totowa, NJ: Barnes & Noble, 1985.

Kraft, M. "The Political and Institutional Setting for Risk Analysis," Risk Evaluation and Management, ed. by V. T. Covello et al., 1986.

Kunreuther, H. C. and E. V. Ley, eds. The Risk Analysis Controversy An Institutional Perspective, New York: Springer-Verlag, 1982.

Lave, L. "Approaches to Risk Management, A Critique," Risk Evaluation and Management ed. by V. T. Covello et al., 1986.

Lee, S. Goal Programming for Decision Making, Philidelphia: Auerbach, 1972.

Lee, S., Introduction to Management Science, New York: The Dryden Press, 1988.

Lee, S., Management by Management Objectives, Princeton: Petrocelli Books, 1981.

Leonard, H. and R. Zeckhauser. "Cost-Benefit Analysis Applied to Risks: Its Philosophy and Legitimacy," Values at Risk, ed. by D. Maclean, 1986.

Lial, M. and C. Miller. Mathematics and Calculus with Applications, Glenview, Illinois: Scott, Foresman and Company, 1979.

Lowrance, W. Of Acceptable Risk: Science and Determination of Safety, Los Altos, CA: William Kaufman, 1976.

Machina, M. "Dynamic Consistency and Non-Expected Utility Models of Choice Under Uncertainty," Journal of Economic Literature, Vol. XXVIII (December 1989), pp. 1622-1668.

Machina, M. "Choice Under Uncertainty: Problems Solved and Unsolved," Journal of Economic Perspectives, Vol. 1, No. 1 (1987), pp. 121-154.

MacLean, D. "Social Values and the Distribution of Risk," Values at Risk, ed. by D. MacLean, 1986.

MacLean, D. ed. Values at Risk, Rowman & Allanheld, 1986.

Mandl, C. and J. Lathrop. "Comparing Risk Assessments for Liquefied Energy Gas Terminals-Some Results," The Risk Analysis Controversy, ed. by H. C. Kunreuther and E. V. Ley, 1982.

Mann, N. R., R. Schafer and N. Singpurwalla. Methods for Statistical Analysis of Reliability and Life Data, New York: John Wiley & Sons, 1974.

Mercer, L. and W. Morgan. "Measurement of Economic Uncertainty in Public Water Resource Development: An Extension," American Journal of Agricultural Economics, May 1978, pp. 241-244.

Moser, D. "An Application of Risk Analysis to the Economics of Dam Safety," Risk-Based Decision Making Water Resources, ed. by Y. Haimes and E. Stakhiv.

Moser, D. "Risk and Uncertainty Analysis Perspectives in Planning." Unpublished paper for the U. S. Army Corps of Engineers, Institute for Water Resources, 1989.

Moser, D. and E. Stakhiv. "Risk-Cost Evaluation of Coastal Protection Projects with Sea Level Rise and Climate Change," Risk Analysis and Management of Natural and Man-Made Hazards, ed. by Y. Haimes and E. Stakhiv, 1989.

National Academy of Engineering. Hazards: Technology and Fairness, Washington D.C.: National Academy Press, 1986.

North, R. "Implementing the Risk and Uncertainty Provisions of the Principles and Standards," Risk/Benefit Analysis in Water Resources Planning and Management, ed. by Y. Haimes, 1981.

O'Connor, P. Practical Reliability Engineering, New York: John Wiley & Sons, 1985.

Okrent, D. "Alternative Risk Management Policies for State and Local Governments," Risk Evaluation and Management, ed. by V. T. Covello et al., 1986.

Page, R. T. and J. Ferejohn. "Improving Risk Analysis," Risk Evaluation and Management, ed. by V. T. Covello et al., 1986.

Pearce, D. W., H. Siebert and I. Walter, eds. Risk and the Political Economy of Resource Development, New York: St. Martin's Press, 1984.

Philipson, L. "Risk Evaluation, A Review of the Literature," Risk Evaluation and Management, ed. by V. Covello et al., 1986.

Poirer, D. J. "Frequentist and Subjectivist perspectives on the Problems of Model Building in Economics," The Journal of Economic Perspectives, Vol. 2, No. 1 (Winter 1988), pp. 121-144.

Ratick, S. and Wei Du. "An Integrated Sensitivity Analysis Approach Procedure for Evaluating Risk and Uncertainty in Local Flood Damage Alleviation." Draft Report for US Army Corps of Engineers, Institute for Water Resources, August 1989.

Rescher, N. Risk, Washington D.C.: University Press of America, 1983.

Risk and Insurance Management Society. Risk Management Glossary, New York: Risk Management Society Publishing, 1985.

Ritter, D. "Risk Analysis Research and Demonstration Act of 1981", 97th Congress H. R. 3441, 1981.

Rowe, W. D. An Anatomy of Risk, New York: John Wiley and Sons, 1977.

Scheaffer, R., W. Mendenhall and L. Ott. Elementary Survey Sampling, North Scituate, MA: Duxbury Press, 1979.

Shrader-Frechette, K. S. Risk Analysis and Scientific Method, Boston: D. Reidel Publishing Co., 1985.

Sjoberg, L., ed. Risk and Society, Boston: Allen & Unwin, 1987.

Slovic, P., B. Fischoff and S. Lichtenstein. "The Psychometric Study of Risk Perception."

Stakhiv, E. "The Status of Risk Analysis in Water Resources Engineering," Risk-Based Decision Making in Water Resources, ed. by Y. Haimes and E. Stakhiv, 1986.

Teweles, Harlow and Stone. The Commodity Futures Game, New York: McGraw-Hill, 1987.

Tobin, R. J. The Social Gamble: Determining Acceptable Levels of Air Quality, Lexington, MA: D.C. Health and Company, 1979.

Tversky, A. and D. Kahneman. "Judgment Under Uncertainty: Heuristics and Biases," Science, Vol. 185 (27 September 1974).

U.S. Army Corps of Engineers, Portland District. Mount St. Helens, Washington-Decision Document: Toutle, Cowlitz and Columbia Rivers, 1985.

U. S. Army Engineer Institute for Water Resources. Handbook of Forecasting Techniques, IWR Contract Report 75-7.

U.S. Nuclear Regulatory Commission. Reactor Safety Study: An Assessment of Accident Risk in U.S. Commercial Nuclear Power Plants, Rasmussen Report WASH-1400, Washington, D.C.: Nuclear Regulatory Commission, 1975.

Van Slyke, R. "Monte Carlo Methods and PERT Problems," Operations Research, Vol.11 (1963), pp. 839-860.

von Neumann, J. and O. Morgenstern. Theory of Games and Economic Behavior, 3rd Ed., Princeton, NJ: Princeton University Press, 1953.

Walpole, R. and R. Myers. Probability and Statistics for Engineers and Scientists, New York: Macmillan Publishing Co., 1978.

Weisbrod, Burton A. "Collective Consumption services of Individual Consumption Goods," Quarterly Journal of Economics, August 1978, pp. 471-477.

Whipple, C. G. "Dealing With Uncertainty About Risk in Risk Management," Hazards: Technology and Fairness, National Academy of Engineering, Washington D.C.: National Academy Press, 1986.

Wonnacott, R. and T. Wonnacott. Econometrics, 2nd Ed., New York: John Wiley & Sons, 1978.

Wonnacott, R. and T. Wonnacott. Introductory Statistics, New York: John Wiley & Sons, 1985.

Yoe, Charles. "The Construction Cost/Risk Cost Trade-Off in Public Works Projects: Navigation Channel width Determination," Risk Analysis and Management of Natural and Man-Made Hazards, ed. by Y. Haimes and E. Stakhiv, 1989.

APPENDIX B

CORPS GUIDANCE ON RISK AND UNCERTAINTY

The basis for risk and uncertainty analysis in Corps planning is found in the U.S. Water Resources Council Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies, March 10, 1983, referred to as P&G. The material in this appendix is excerpted from relevant sections of the P&G.

From page v:

10. Risk and Uncertainty

Planners shall identify areas of risk and uncertainty in their analysis and describe them clearly, so that decisions can be made with knowledge of the degree of reliability of the estimated benefits and costs and of the effectiveness of alternative plans.

Chapter I - Standards, Section IV - General Planning Considerations:

1.4.13 Risk and Uncertainty--Sensitivity Analysis.

(a) Plans and their effects should be examined to determine the uncertainty inherent in the data or various assumptions of future economic, demographic, social, attitudinal, environmental, and technological trends. A limited number of reasonable alternative forecasts that would, if realized, appreciably affect plan design should be considered.

(b) The planner's primary role in dealing with risk and uncertainty is to identify the areas of sensitivity and describe them clearly so that decisions can be made with knowledge of the degree of reliability of available information.

(c) Situations of risk are defined as those in which the potential outcomes can be described in reasonably well-known probability distributions such as the probability of particular flood events. Situations of uncertainty are defined as those in which potential outcomes cannot be described in objectively known probability distributions.

(d) Risk and uncertainty arise from measurement errors and from the underlying variability of complex natural, social, and economic situations. Methods of dealing with risk and uncertainty include:

(1) Collecting more detailed data to reduce measurement error.

(2) Using more refined analytic techniques.

(3) Increasing safety factors in design.

(4) Selecting measures with better known performance characteristics.

(5) Reducing the irreversible or irretrievable commitments of resources.

(6) Performing a sensitivity analysis of the estimated benefits and costs of alternative plans.

(e) Reducing risk and uncertainty may involve increased costs or loss of benefits. The advantages and costs of reducing risk and uncertainty should be considered in the planning process. Additional information on risk and uncertainty can be found in Supplement 1 to this chapter.

Supplement I

Risk and uncertainty--Sensitivity analysis

Uncertainty and variability are inherent in water resources planning. For example, there is uncertainty in projecting such factors as stream flows, population growth, and the demand for water. Therefore, the consideration of risk and uncertainty is important in water resources planning.

This supplement provides guidance for the evaluation of risk and uncertainty in the formulation of water resources management and development plans.

S1 Concepts.

(a) *Risk.* Situations of risk are conventionally defined as those in which the potential outcomes can be described in reasonably well known probability distributions. For example, if it is known that a river will flood to a specific level on the average of once in 20 years, a situation of risk, rather than uncertainty, exists.

(b) *Uncertainty.* In situations of uncertainty, potential outcomes cannot be described in objectively known probability distributions. Uncertainty is characteristic of many aspects of water resources planning. Because there are no known probability distributions to describe uncertain outcomes, uncertainty is substantially more difficult to analyze than risk.

(c) *Sources of risk and uncertainty.* (1) Risk and uncertainty arise from measurement errors and from the underlying variability of complex natural, social, and economic situations. If the analyst is uncertain because the data are imperfect or the analytical tools crude, the plan is subject to measurement errors. Improved data and refined analytic techniques will obviously help minimize measurement errors.

(2) Some future demographic, economic, hydrologic, and meteorological events are essentially unpredictable because they are subject to random influences. The question for the analyst is whether the randomness can be described by some probability distribution. If there is an historical data base that is applicable to the future, distributions can be described or approximated by objective techniques.

(3) If there is no such historical data base, the probability distribution of random future events can be described subjectively, based upon the best available insight and judgment.

(d) *Degrees of risk and uncertainty.* The degree of risk and uncertainty generally differs among various aspects of a project. It also differs over time, because benefits from a particular purpose or costs in a particular category may be relatively certain during one time period and uncertain during another. Finally, the degree of uncertainty differs at different stages of the analysis--for example, between rough screening and final detailed design, when more precise analytic methods can be applied.

(e) *Attitudes.* The attitudes of decisionmakers toward risk and uncertainty will govern the final selection of projects and of adjustments in design to accommodate risk and uncertainty. In principle, the government can be neutral toward risk and uncertainty, but the private sector may not be. These differences in attitudes should be taken into account in estimating the potential success of projects.

S2 Application.

(a) *The role of the planner.* (1) The planner's primary role in dealing with risk and uncertainty is to characterize to the extent possible the different degrees of risk and uncertainty and to describe them clearly so that decisions can be based on the best available information. The planner should also suggest adjustments in design to reflect various attitudes of decisionmakers toward risk and uncertainty. If the planner can identify in qualitative terms the uncertainty inherent in important design, economic, and environmental variables, these judgments can be transformed into or assigned subjective probability distributions. A formal model characterizing the relationship of these and other relevant variables may be used to transform such distributions to exhibit the uncertainty in the final outcome, which again is represented by a probability distribution.

(2) At all stages of the planning process, the planning can incorporate any changes in project features that, as a result of information gained at that stage, could lead to a reduction in risk and uncertainty at a cost consistent with improvement in project performance.

(b) Some risk and uncertainty are assumed in nearly every aspect of a water resources project. Some types of risk and uncertainty are dealt with in terms of national planning parameters--for example, ranges of population projections and other principal economic and demographic variables. Other types of risk and uncertainty are dealt with in terms of project or regional estimates and forecasts. When projects are related to other projects and programs in their risk and uncertainty aspects (e.g., interrelated hydrologic systems), reasonable attempts should be made to see that the same analyses and presumed probability distributions are used for all of them.

(c) The risk and uncertainty aspects of projects are likely to be seen and analyzed differently as planning proceeds from rough screening to detailed project proposals. An effort should be made, therefore, to relate the techniques used in characterizing and dealing with risk and uncertainty to the stage of the planning process.

(d) The resources available for analyzing aspects of risk and uncertainty should be allocated to those assessments that appear to be the most important in their effects on project and program design. Rather than assuming in advance that one or an other variable is a more important source of risk and uncertainty, the planner should make a thorough effort to determine which variables will be most useful in dealing with measurement errors and natural sources of risk and uncertainty.

(e) The aspects of project evaluation that can be characterized by a probability distribution based on reasonably firm data, such as hydrologic risk, can be treated by standard methods of risk evaluation developed by Federal agencies and others.

(f) Most risk and uncertainty aspects of projects cannot be characterized by probability distributions based on well established empirical data. A first step in dealing with this problem is to describe why the project or specific aspects of it are uncertain, as well as the time periods in which different degrees of uncertainty are likely. A range of reasonably likely outcomes can then be described by using sensitivity analysis--the technique of varying assumptions as to alternative economic, demographic, environmental, and other factors, and examining the effects of these varying assumptions on outcomes of benefits and costs. In some cases and in some stages of planning, this approach, when accompanied by a careful description of the dimensions of uncertainty, will be sufficient. It can be accompanied by descriptions of design adjustments representing various attitudes toward uncertainty.

(g) It may be appropriate in some cases to characterize probability estimates, but the project report should make clear that the numerical estimates are subjective. Moreover, subjective probability distributions should be chosen and justified case by case, and some description of the impact on design of other subjective distributions should be given. Design alternatives reflecting various attitudes toward uncertainty may be suggested.

(h) Utility functions may be used in conjunction with assessments of uncertainty to explore design adaptations reflecting specific preferences. Public preferences, if well known, may be used to illustrate to decisionmakers what the best design would be, given the uncertainties and preferences in a particular case. If public preferences are not well known, justification could be given for the selection of various utility functions, which can be used only to illustrate the effects on design of various preferences.

(i) At each level of analysis, the planner should take into account the differences in risk and uncertainty among project purposes and costs, among various time periods, and among different stages of planning.

(j) Adjustments to risk and uncertainty in project evaluation can be characterized as general or specific. General adjustments include the addition of a premium rate to the interest, overestimation of costs, underestimation of benefits, and limitations on the period of analysis. Such general adjustments are usually inappropriate for public investment decisions because they tend to obscure the different degrees of uncertainty in different aspects of projects and programs. Specific adjustments--including explicit assessments of different degrees of risk and uncertainty in specific aspects of a project or program and specific adjustments to them--are preferable. Additional information on methods of dealing with risk and uncertainty can be found in Section 1.4.13(d) of Chapter 1.

(k) One guide to the use of the techniques discussed here is displayed in Table S-2. In general, more complex techniques are appropriate as planning proceeds from the initial development and the screening of alternatives to the analysis and presentation of the final set of alternative plans. For example, sensitivity analysis--testing the sensitivity of the outcome of project evaluation to variation in the magnitude of key parameters--may be most useful and applicable in the early stages of planning, when the concern is to understand single factors or relatively general multiple-factor relationships. Multiple-factor sensitivity analysis, in which the joint effects or correlations among underlying parameters are studied in greater depth, may be more appropriate in the detailed analytic stage than in the screening stage.

(l) Similarly, analysis of risk and uncertainty based on objective or subjective probability distributions would be more appropriate in the detailed analytic stage than in the early screening stage. Although hydrologic and economic probabilities may be used in the screening stage, the full use of independent and joint probability distributions, possibly developed from computer simulation methods, to describe expected values and variances, is more appropriately reserved for the detailed stage.

(m) Although decisionmakers' attitudes and decision rules can be used to give perspective on alternative designs throughout the planning process, they are more appropriate at the stage of displaying alternative designs.

(n) The differences among the underlying degrees of risk and uncertainty, the design adaptations to them, and the preferences of decisionmakers should be kept clear throughout the analysis. The first two depend primarily on technical expertise; the last is the set of preferences based on various attitudes toward risk and uncertainty.

S3 Report and display.

The assessment of risk and uncertainty in project evaluation should be reported and displayed in a manner that makes clear to the decisionmaker the types and degrees of risk and uncertainty believed to characterize the benefits and costs of the alternative plans considered.

Table S-2–Planning Task and Approaches to Risk and Uncertainty

	Screening alternatives	Detailed analysis of projects	Final presentation of alternatives
Sensitivity analysis	X	X	X
Use of objective and subjective probability distributions		X	X
Illustrative application of public preferences and decisionmakers' attitudes		X	X

APPENDIX C

BASIC CONCEPTS OF PROBABILITY

INTRODUCTION

In water resources planning, as with most of life's ventures, it would be very useful if we could predict how things will turn out if we chose one action or thing rather than another or alternative. Unfortunately, it is impossible to do this in all but the most trivial circumstances. Probability theory provides a tool for dealing with many of life's situations that are not certain.

In this appendix, basic concepts of probability are presented more intuitively than rigorously. The concepts emphasized are those that are most useful in dealing with risk and uncertainty analysis.

DEFINITION OF PROBABILITY

The probability that a two-year flood or greater will occur in any year is ½. It is not as easy to determine what that means philosophically as one might think.

According to the relative frequency view of probability, this statement means that if we looked at flood records over many years we would find that the number of years that had a two-year flood would be close to half the years we considered, provided a sufficiently large number of years was considered.[1] Does this mean probability is nothing more than relative frequency? In some cases, a relative frequency interpretation of probabilistic events is difficult to interpret. The probability that "this" dam will fail is an example. We cannot build the same dam in the same location hundreds of times and see which ones fail. Thus, relative frequency interpretations of probabilities may not be applicable in all cases.

The subjective view of probability states that probability is an estimate of what an individual thinks is the likelihood that an event will happen. Subjective probabilities make it possible to consider a wider class of probabilistic events, such as dam failures. The problem is that probabilities become less tangible because we can't objectively specify what the probabilities are.

A random event is one in which any particular outcome is uncertain. The main characteristic of a random event is that no one way to predict the outcome of an event is any better or any worse than another.

To determine the probability of a random event we need to define a few terms. First, we'd like a list of all the possible outcomes of the event we are interested in. The set that contains all of the possible outcomes of a random event is called the probability space, designated by **S**.[2] It

[1] Actually it is a two-year flood or greater. We neglect emphasizing this very important point here in order to get the basic notion of a frequentists view of probability across. The matter of probability distributions is taken up again in Appendix D.

[2] Sometimes called the sample space.

is important that every single possible outcome of the event be included in **S**. The total number of possible outcomes is designated by **s**. Assuming each outcome is equally likely the probability of any one outcome is **1/s**.

To illustrate, consider the random event to be the determination of the value of any one house in a flood plain. The probability space is the value of every house in the flood plain. If a flood plain has 1,000 houses, the probability of choosing any one house is 1/1000 or .001.

An event, **A**, is a set that consists of a group of outcomes. In the flood plain example, **A** could be the set of all houses with a value of $35,000 (say, 100 houses). Each house is an outcome and the set of them is an event. An event is a subset of the probability space.

The probability of an event **A** (choosing a house worth $35,000) is the number of outcomes in the set **A** (the number of houses worth $35,000), designated N(A), divided by the total number of possible outcomes s. Thus probability, **p**, is formally defined:

(1) $p(A) = N(A)/s$

In the flood plain example $p(A) = 100/1000 = 0.1$.

BASIC CONCEPTS IN PROBABILITY THEORY

Range of Probability

What is the probability that event **S** will occur? Because **S** contains all the possible outcomes of the random event using (1) we have:[3]

(2) $p(S) = N(S)/s = s/s = 1$

The probability is 100 percent that the outcome or result of the random event will be one of the possible results.

What is the possibility that the event contains no outcomes? The probability of nothing happening is zero:

(3) $p(\varnothing) = 0$.

These two results yield the familiar range for a probability as being between zero and one.

Sometimes we may know the probability of an event not happening. Fortunately, the above results make it easy to obtain the probability that something will happen given the probability that it won't. The outcomes that are not in the set **A** are in the complement of that set, $\mathbf{A^c}$. Thus:

(4) $p(A^c) = 1 - p(A)$

---

[3] It is important that those not familiar with the terminology of probability theory keep the meaning of terms straight. A random event is not the same as an event. Random events are often called experiments to avoid this confusion in terms.

In our example, given the probability that the value of the house chosen is \$35,000 is 0.1, it is straightforward to calculate that the probability that the value is not \$35,000 is 0.9.

Probability of a Union

Disjoint Events. What is the probability that the house chosen is worth \$35,000 or \$40,000? Let **B** be the event that a house is worth \$40,000 (say there are 200 such houses). We know p(A) = 0.1 and p(B) = 0.2 since there are 1000 houses. Because a house can't be worth exactly \$35,000 and \$40,000 these two events, **A** and **B**, are disjoint (or mutually exclusive). Two events that cannot occur together are called disjoint. The probability that the house chosen is one of these two values is simply the sum of their disjoint probabilities.

(5) $p(A \text{ or } B) = p(A) + p(B)$

This is the probability of a union of two disjoint events.

Joint Events. Now consider the example where we want to know the probability of choosing either a one-story house or a house worth \$35,000. The probability of selecting a \$35,000 house is 0.1. If 500 houses are one-story, the probability of the event **B**, the house is one story, is 0.5. Suppose 45 of the \$35,000 houses are one-story houses. How do we calculate the probability of the outcome of a \$35,000 or one-story house?

We are after the number of \$35,000 houses plus one-story houses less the number of houses that are both, to avoid double-counting.[4] The number of satisfactory outcomes is given by:

(6) $N(A \cup B) = N(A) + N(B) - N(A \cap B)$

The probability of an outcome that is **A** or **B** is given by:

(7) $p(A \text{ or } B) = p(A) + p(B) - p(A \cup B)$ or
$p(A \cup B) = p(A) + p(B) - p(A \cap B)$

This formula is valid for any two events, joint or disjoint.[5] In our example we have:

(8) p(\$35,000 or 1-story) = 0.1 + 0.5 - .045 = .555

This computation is illustrated in the probability space Venn diagram in Figure C-1.

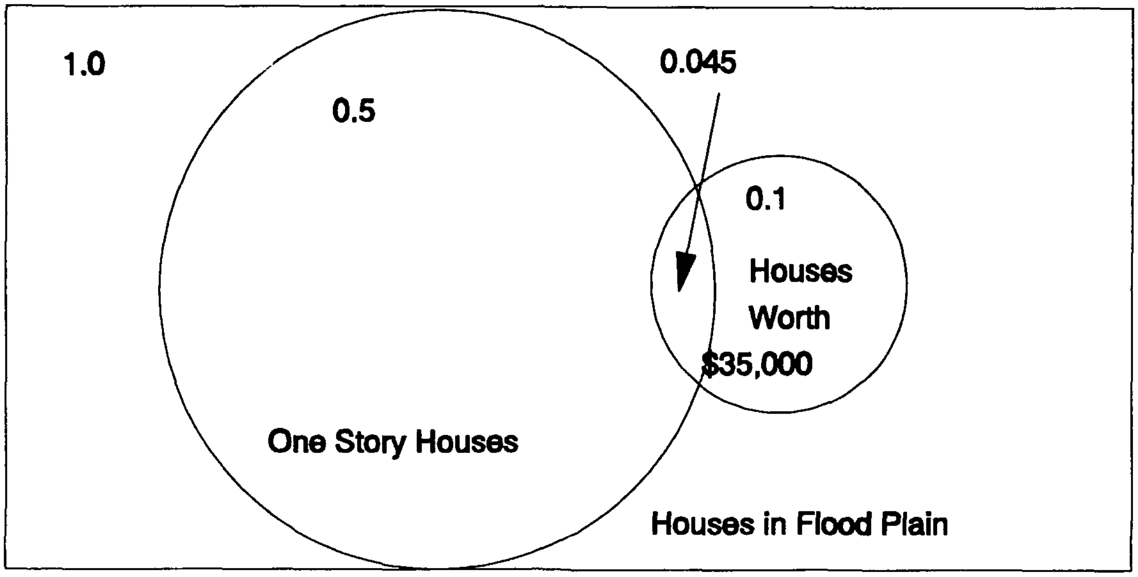
This formula can be expanded indefinitely. To determine the union of three events use:

(9) $p(A \cup B \cup C) = p(A) + p(B) + p(C) - p(A \cap B) - p(B \cap C)$
$- p(A \cap C) + p(A \cap B \cap C)$

---

[4] Outcomes that belong to both event spaces are members of the intersecting set or space, $\mathbf{A \cap B}$.

[5] Note that the probabilities in (7) can be manipulated according to the laws of algebra. The probability of a house being in both event spaces is given by: $p(A \cap B) = p(A) + p(B) - p(A \bar{\cup} B)$.



Note: Not drawn to scale

Figure C-1: Joint Probability Venn Diagram

To illustrate this consider the probability of a selecting a house worth \$35,000 (A), with one-story (B), in the ten-year flood plain (C). Of our 1000 houses, suppose that 600 houses are in the ten-year flood plain and 300 of them are one-story, 75 are worth \$35,000, and 30 are both one-story and worth \$35,000. Using formula (9), we can compute $p(A \cup B \cup C)$ as follows:

$$p(A \cup B \cup C) = 0.1 + 0.5 + 0.6 - 0.045 - 0.3 - .075 + .03 = 0.81$$

Thus, there is an 81 percent chance that the house chosen will behave at least one of the following characteristics: worth \$35,000, one-story, or in ten-year flood plain.

Figure C-2 illustrates this calculation. Areas have been labeled to correspond to the various probabilities. The arguments in equation (9) are defined by the following areas:

$$p(A) \equiv s + t + x + y$$
$$p(B) \equiv s + v + w + x$$
$$p(C) \equiv s + t + u + v$$
$$p(A \cup B) \equiv x + s$$
$$p(B \cup C) \equiv s + v$$
$$p(A \cup C) \equiv s + t$$
$$p(A \cup B \cup C) \equiv s$$

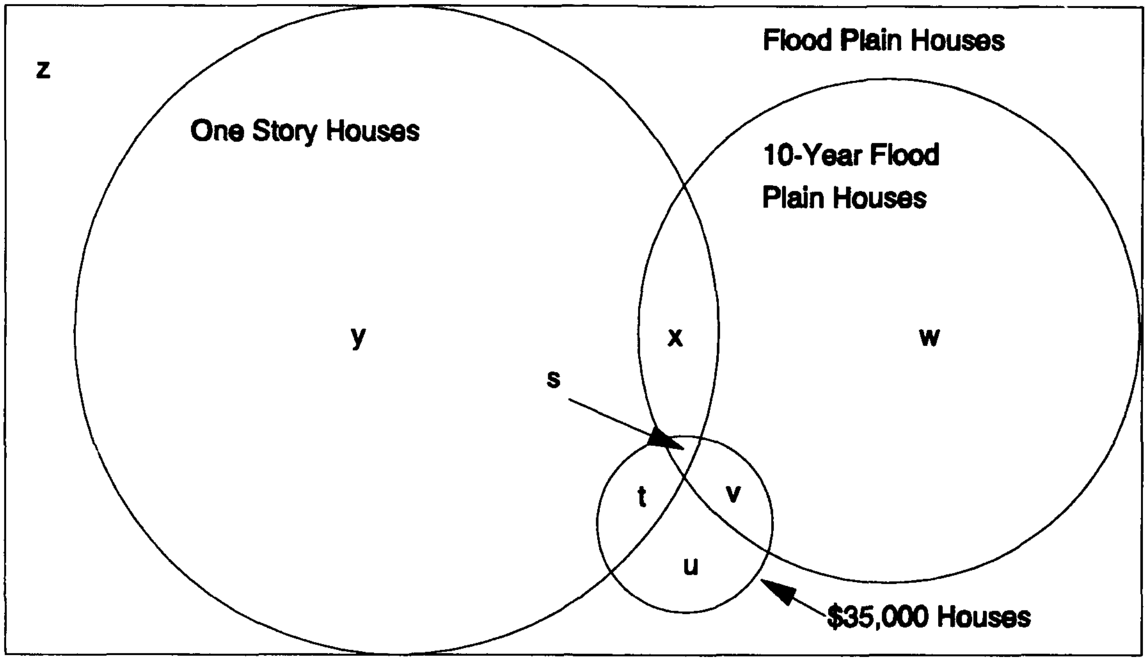


Figure C-2: Three Event Joint Probability Venn Diagram

The right hand side of equation (9) becomes: s + t + x + y + s + v + w + x + s + t + u + v - x - s - s - v - s - t + s. Carrying out the algebra this reduces to: s + t + u + v + w + x + y; which is the area of the three circles (sets) devoid of any double counting as shown in the diagram.

The pattern for expanding this formula for **n** events is:

1) Add the probabilities of all n events individually.
2) Subtract the probabilities of the intersections of all possible pairs of events.
3) Add the probabilities of all possible intersections of the events taken three at a time.
4) Subtract the probabilities of all possible intersections of the events taken four at a time.

The add/subtract pattern continues.

Conditional Probability

A conditional probability is the probability that one particular event will occur given that another specific event has occurred. Conditional probabilities are written $p(A \mid B)$ and read as the probability of **A** given that **B** will occur.

For example, a conditional probability tells us the probability that a house is worth $35,000 given that we know it is a one-story house. We know there are 100 houses worth $35,000. With the conditional probability $p(A \mid B)$ we know that not all of those 100 houses are possible. Some of them are two-story houses and they have been eliminated from the event space when we learned that event **B**, the house is one story, had already been obtained. The number of outcomes in which event **A**, the house is worth $35,000, can occur is equal to the number of outcomes that are in both event spaces. We have already defined this set as $(A \cap B)$ and in our example it is 0.045.

The knowledge that **B** will occur tells us we are now dealing with 500 houses. Forty-five of these are worth $35,000. Thus the conditional probability is defined as follows:

(10) $p(A \mid B) = p(A \cap B)/p(B)$

In our example this is $.045/.5 = .09$.

Independent Events

Knowing that one event will occur will often tell us if another event is more or less likely. However, there are some cases in which knowing one event will occur tells us absolutely nothing about the likelihood of another event. In such a case the events are independent. If A and B are independent events independence is defined:

(11) $p(A \mid B) = p(A)$

Equation (11) is a useful result. Using it and (10) we obtain the following when events A and B are independent:

(12) $p(A) = p(A \cap B)/p(B)$

With simple manipulation we get:

(13) $p(A \cap B) = p(A)\, p(B)$

This tells us that when two events are independent the probability of them both occurring together is the product of their probabilities.

The usefulness of some of these results can be seen in an example of independent events as illustrated by the problem of coincident flooding. Suppose a business district can be flooded by a small creek that runs right through its middle and by the river, several blocks away, to which the creek is a tributary. The creek has a small local drainage area. The river drains thousands of square miles. Floods from the two sources are independent of one another. The creek may flood from a local thunderstorm, giving no information about possible river flooding. A tropical storm dumping rain on the upper river basin may cause river flooding and tell us nothing about the creek.

If we are estimating expected annual damages we want the probability that flooding occurs from either source less the probability that it occurs from both sources (equation (7)). If the creek floods and the river floods to the same stage soon after, the damage will have been done by the creek. We do not want to double count damages.

Suppose the probability of the creek reaching a flood stage of +10 is .05 and the probability of the river reaching +10 is .1. The probability of water reaching +10, then, is .05 plus .1 minus the probability that both the creek and river flood. And what is that probability? Given these are independent events it is calculated by (13). Thus flooding from both sources reaches a stage of +10 with the probability 0.05 + 0.1 -.005 = 0.145. This calculation would be done for each flood stage.

AXIOMS OF PROBABILITY

To summarize this brief introduction to some basic concepts in probability theory a more formal (but less than rigorous) presentation of a mathematical model of probability is offered.

Beginning with the probability space **S** and any event **X** (i.e., **X** is a subset of S) the three basic axioms are:

Axiom 1: $p(S) = 1$
Axiom 2: $p(X) \geq 0$
Axiom 3: Given disjoint events A and B, then $p(A \cup B) = p(A) + p(B)$

Using these axioms the following theorems can be proven.[6]

Theorem 1: $p(X) \leq 1$, for any event X
Theorem 2: $p(A^C) = 1 - p(A)$
Theorem 3: $p(\emptyset) = 0$
Theorem 4: $p(A \cup B \cup C) = p(A) + p(B) + p(C)$, for disjoint events A, B and C
Theorem 5: $p(A \cup B) = p(A) + p(B) - p(A \cap B)$

[6] Proof of these theorems can be found in most basic probability and statistics texts.

APPENDIX D

DISTRIBUTIONS

INTRODUCTION

The uncertain events planners are interested in often involve counting or measuring something. For example, in conducting damage surveys we are interested in counting houses and measuring their value. In analyzing such cases it is often easier to talk about random variables than it is to worry about the terminology of probability theory and its events, probability spaces, and so on.

Two key concepts in understanding and analyzing uncertain situations in the context considered in this appendix, are:

1) random variables, and
2) the probability that a random variable will take a specific value.

A random variable is one that takes on a specific value when a particular random event occurs.[1] A random variable is a member of a set consisting of all possible values the variable can take. A function defining a relationship among variables determines the value the random variable takes. The function may or may not be known.[2] Although the actual value of a random variable may not be known, the probability that it will equal a particular value can often be calculated.

Many risk and uncertainty assessment techniques rely on an understanding of the distribution of a random variable, the subject of this appendix. The presentation is introductory rather than rigorous. A number of excellent text books are available to provide additional details to the reader.[3]

Random variables are generally divided into discrete and continuous random variables. Random variables that can take on only certain isolated values are called discrete random

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[1] Thus, it is formally a function from sets to numbers.

[2] As an illustration, consider the market value of a flood plain structure as a random variable. Market is a function of many variables, e.g., age, size, location, flood risk, condition, etc. We may not know how the many variables interact to determine the value the random variable market value takes, but we can observe that value and the probability that a house will have a certain value or higher.

[3] One text of particular value to any practitioner who will work with probability density functions is A Guide to Probability Theory and Application by Cyrus Derman, et al (1973). Unfortunately, the book is no longer in print but it is well worth the effort of a search for any non-statistician.

variables.[4] Random variables that can take on any value over a specified range are called continuous random variables.[5]

Statistical texts normally present discrete and continuous variables separately. The math of discrete functions is normally presented with summations rather than the calculus necessary for continuous functions. In the interests of brevity no such distinction is made here in the presentation of probability density and cumulative distribution functions. The reader is forewarned that there are subtle and not so subtle distinctions between discrete and continuous functions that are not completely developed in this text.

PROBABILITY DENSITY FUNCTIONS

It is necessary to know which values of random variables are possible and which are not, in order to address the question of the likelihood of each value. In some cases, where we understand the process that is creating the values of a random variable, it is easy to calculate the probability of each value. Several hundred years of stream records makes it relatively simple to estimate the probability of a given flow. In other cases where the processes involved are more complex, such as in calculating the probability of a dam failure, it is more difficult to calculate probabilities.

A probability density function[6] or PDF for a random variable provides useful information about the values the variable can take. The value of a function is a number. The value of the probability density function (or probability mass function) for a particular value of the random variable is the probability that the random variable will equal that number. The PDF of a discrete random variable is defined as:

(1) $f(a) = p(X = a)$

where f stands for the PDF,
X is the random variable,
a is the numeric value it takes, and
p is probability.

Equation (1) simply says that the probability that a random variable **X** takes the specific value **a** is given by the number **f(a)**. For instance, if **X** is the random variable, barges per tow, and **a** is the value 15 barges, then **f(a)** is the probability that a tow has 15 barges.

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4 Examples of discrete random variables include the number of stories a house can have, the number of houses in a flood plain or the number of barges in a tow.

5 Examples include streamflow, tonnage, kilowatt hours of power produced, etc. Tonnage shipped through a lock in a year is a continuous random variable that could take the value 14.98 or 14.981 million tons, as well as any other of an infinite number of values.

6 It is useful to bear in mind that a function is not a number/single value, it is a relationship between/among variables.

There is a close connection between the density function and a frequency diagram (or histogram). A frequency diagram is constructed from historical or experimental data. It simply shows the number of times a random variable takes a specific value. The frequency diagram has approximately the same shape as the density function if there is a sufficiently large number of observations. The number of times a value is observed divided by the number of observations provides a frequency that is often used as an estimate of the true probability of that value being obtained. True probability is the limiting value, the value the frequency approaches as the number of observations approaches infinity. A density function provides the true probability, frequency distributions provide an estimate of the true probability.

The PDF for a continuous random variable has a characteristic that distinguishes it from a discrete random variable PDF that is worth noting. While we can know the probability that a discrete random variable takes on a specific, single value, the probability that any continuous random variable will take on any specific, precise value is zero. For example, there is an infinite number of possible stream flows, limited only by our ability to measure them. We could observe flows of 100 cfs, 100.001, 100.002, etc. This means that:

(2) $p(X = 100) = 1/\infty = 0$

This being the case, we use the PDF of a continuous random variable to tell us the probability that the random variable falls within a certain range of values.

The area under the function between two values is the probability that the random variable will take a value between those two values. The expression "area under the PDF f(x) from **a** to **b**" can be written mathematically as the integral:

(3) $\int_{b}^{a} f(x)dx.$

The total area beneath the PDF f(x) must equal one.

CUMULATIVE DISTRIBUTION FUNCTION

At times we want to know the probability that a random variable **X** will be less than or equal to a particular value **a**. For example, the natural streambank can contain a flow of size **a** and any lesser flows. The probability that a flow is equal to or less than **a** is a measure of the level of natural flood protection provided by the bank.

A function that tells us the probability that a random variable **X** will be less than or equal to a particular value is called the cumulative distribution function or CDF. The CDF is represented by a capital F and is defined as:

(4) $F(a) = p(X \leq a)$

If we want to find the probability that **X** will be greater (note that it is not equal or greater) than a particular value we simply manipulate equation (4) with the knowledge that the probability of all events must sum to one to get:

(5) $p(X > a) = 1 - p(X \leq a) = 1 - F(a)$

This is the survival function. Flood frequency curves are based on this relationship. A 100-year flow has an annual probability of 0.01 that a flow of its size or greater will occur.[7]

To find the probability that the value of **X** will fall between two particular values use the formula:

(6) $p(b < X < c) = F(c) - F(b)$

This formula could be used to determine the probability that a flow greater than the natural level of protection but less than the proposed project level of protection would occur.

Cumulative distribution functions satisfy the following properties:

1) F(a) is always between 0 and 1, $0 \leq F(a) \leq 1$.
2) As **a** becomes very large, F(a) approaches 1, limit F(a) = 1.
3) As **a** becomes very small, F(a) approaches 0, limit F(a) = 0.
4) F(a) is never decreasing, i.e., F is monotonically increasing.
5) F(a) for a discrete random variable is piecewise continuous. Its graph looks like an irregular staircase.

PDFs, CDFs, AND OTHER FUNCTIONS

It is worth noting that the PDF and CDF contain the same information. The area under the PDF is the probability a random variable will take a value between the values that determine the lower and upper limits of the area under the PDF being computed. The height of the CDF is the probability a random variable will be less than or equal to a given value. Given either of these functions, it is possible to generate the other through sometimes complex mathematical manipulations.

To illustrate the link between the PDF and CDF consider the case where we want to know the probability that a flow between 100 and 1000 cfs will occur for a particular stream. Using the PDF f(x) one need only compute the area under the curve between 100 and 1000 cfs. Mathematically this is expressed as:

[7] To be consistent with the mathematical definition of the survival function it is better to the probability of a flow greater than a flow arbitrarily close to but less than (say, for example, a 99.9999999-year flow) the 100-year flow has an annual probability of 0.01 of occurring.

$$(7) \int_{100}^{1000} f(x)dx.$$

Using the CDF, F(x), the exact same probability will be obtained by computing:

(8) $F(1000) - F(100)$

A third function that can be derived from the parameters of a PDF is the survival function S(x). This function was defined above as (1 - CDF) for a value **a**, or:

(9) $S(a) = 1 - F(a)$

In some cases, the lifetime of a system, phenomenon, item, or individual is observed and of interest. For example, we may be interested in the probability that a stall (an unplanned closure) at a lock lasts more than 12 hours. The CDF gives the probability the stall is 12 hours or less. The survival function gives the probability the stall lasts more than 12 hours. The survival function is sometimes called the survival cumulative distribution function or SCDF.

A fourth derivable function is the hazard function H(x). It is defined as the PDF over the SCDF for any value **a**, or:

(10) $H(a) = f(a)/S(a)$

The hazard function is useful in considering the duration of events. The hazard function is the rate at which events will be completed at time **a**, given they last until time **a**. In other words, the hazard function gives the probability that a stall that lasts 12 hours will end shortly after 12 hours. Increasing hazard means that the probability an event will end soon increases as the event increases in duration. Decreasing hazard means the probability an event will end soon decreases as the event increases in duration.

CONTINUOUS RANDOM VARIABLE DISTRIBUTIONS

Table D-1 summarizes several commonly used continuous variable PDFs. To assist the non-statistician's understanding of distributions, parameters, and functions the best known distribution, the normal distribution, will be considered in more detail.

We have all seen the "bell-shaped" curve, which is the normal distribution. The form of the normal distribution was discovered early in probability history because it arose as the answer to an important theoretical problem. It soon became of interest to scientists in a variety of disciplines because it seemed to describe the variation from observation to observation of many quantitative phenomena.

The distribution of data in a typical normal distribution are reasonably well characterized by the function:

Name	Range	Parameters	PDF	Expectation	Variance
Continuous Uniform	$a<x<b$	$a,\ b$	$f(x) = \frac{1}{b-a}$	$\frac{a+b}{2}$	$\frac{(b-a)^2}{12}$
Normal	$-\infty<x<\infty$	$\mu,\ \sigma^2$	$f(x)=\frac{1}{\sigma\sqrt{2\pi}}\, e^{-[(x-\mu)/2\sigma]^2}$	μ	σ^2
Lognormal	$0<x$	$\mu,\ \sigma^2$	$f(x)=\frac{1}{x\sigma\sqrt{2\pi}}\, e^{-[(\ln x-\mu)/2\sigma]^2}$	$e^{(\mu+\sigma^2/2)}$	$e^{2\mu+\sigma^2}\ (e^{\sigma^2}-1)$
Negative Exponential	$0<x$	$\lambda>0$	$f(x) = \lambda e^{-\lambda x}$	$\frac{1}{\lambda}$	$\frac{1}{\lambda}$

Table D-1: Continuous Random Variable Probability Density Functions

(11) $f(x) = e(-(1/2)x^2)$

Because we may want to adjust the peak and shape of the distribution we add two parameters to the function. To adjust the peak we add the mean of the distribution, μ. To adjust the shape we add the standard deviation of the distribution, σ. The new function with these adjustments is:

(12) $f(x) = e^{(-1/2((x-\mu)/\sigma)^2)}$

This function can only be a true probability function if the area under it is equal to one. The area under the function in equation (14) turns out to be $((2\pi)^{.5})\sigma$. So we need to divide by $((2\pi)^{.5})\sigma$ to make the area equal 1. The density function for a normal random variable is defined as:

(13) $f(x) = (1/((2\pi)^{.5})\sigma)e^{(-1/2((x-\mu)/\sigma)^2)}$

It is particularly helpful for the analyst to understand the number and nature of parameters in a distribution.[8] Knowing how a change in one parameter or another affects the distribution will greatly aid understanding in working with distributions.

Figures D-1, D-2, D-3, and D-4 present the PDF, CDF, SCDF, and hazard function for normal distributions with $\mu = 100$ and $\sigma = 50$ and $\mu = 50$ and $\sigma = 40$ to illustrate how the functions can change when the parameters change.

DISCRETE RANDOM VARIABLE DISTRIBUTIONS

Table D-2 summarizes several commonly used discrete variable PDFs. The binomial distribution is considered here to illustrate its potential use in water resources planning.

Suppose we conduct a Bernoulli trial, a random experiment of **n** independent trials with two possible outcomes, usually called "success" and "failure".[9] It would be interesting to consider a random variable Z, the number of successes in the **n** trials. Z is a discrete variable that can assume any of the values 0, 1, 2, ..., **n**.

Suppose we look at three years to see if a 100-year flood occurred. We could see any of the following 8 outcomes where S = flood (success) and F = no flood (failure):

(S,S,S), (S,S,F), (S,F,S), (F,S,S), (F,F,S), (S,F,F), (F,S,F), and (F,F,F).

---

[8] It is also helpful to keep the distinction between distributions and distribution functions clear. A function is a mathematical relationship. A distribution is simply the spread of the data or the frequency with which it takes all its possible values.

[9] Whenever we have a random event with two possible outcomes we have a Bernoulli trial. We have a Bernoulli trial if we are interested in whether a 100-year flood did or did not occur in a given year. Because there are two possible outcomes in a Bernoulli trial they are often arbitrarily called "success" and "failure".

The values of **Z** corresponding to these outcomes are: 3, 2, 2, 2, 1, 1, 1, 0. To find the appropriate probability model for **Z** we have to find the probabilities of the different events. To illustrate, let E_1 be the event "success on the first trial", E_2 the event "success on the second trial", and E_3 the event "success on the third trial." Then the probability of (S,S,S) is :

(14) $p(S,S,S) = p(E_1)p(E_2)p(E_3) = p^3$

If the event we are interested in is the occurrence of a 100-year flood we know it has an annual probability of 0.01. Thus, the probability in equation (16), of observing three 100-year floods in three years is .000001. The density function for a binomial distribution is:

(15) $\binom{n}{x} \quad p^x(1 - p)^{n-x}$

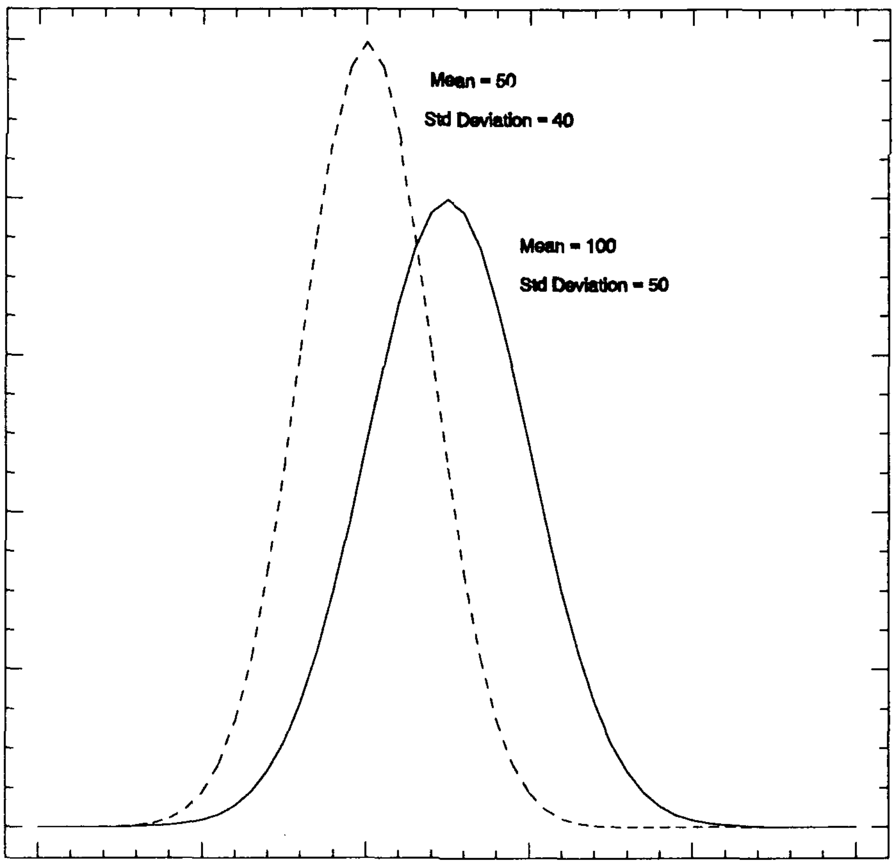

Figure D-1: Probability Density Functions--Normal Distribution

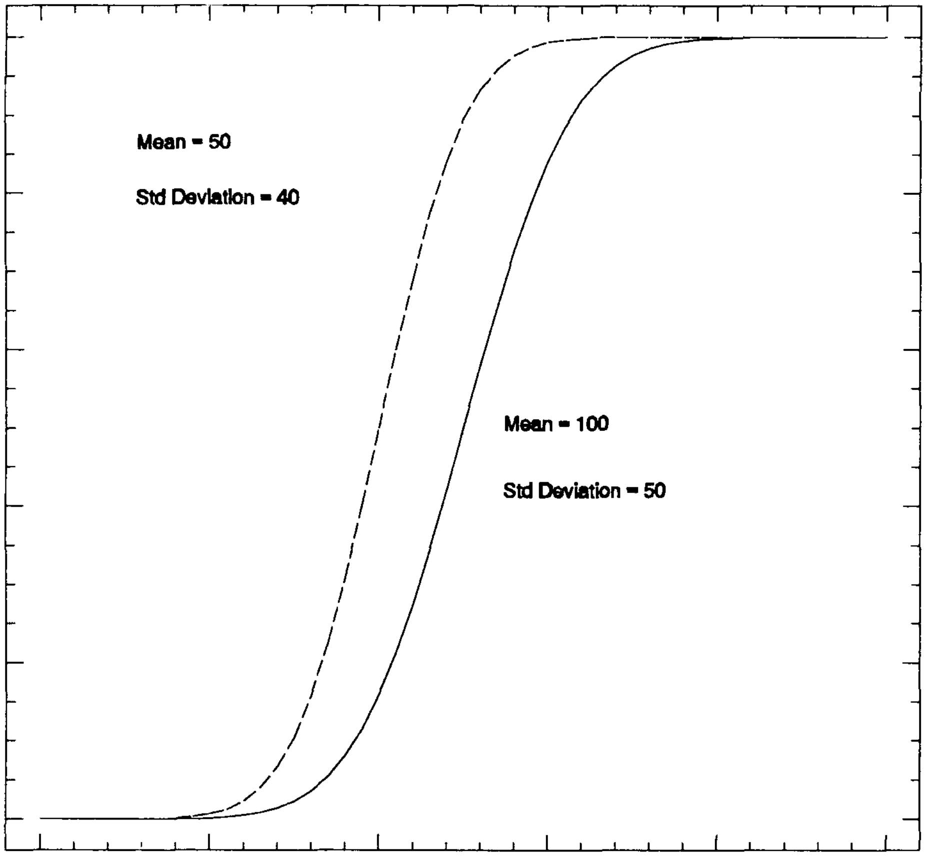

Figure D-2: Cumulative Distribution Functions--Normal Distribution

Where **n** is the number of trials (three years in this example) and **x** is the number of successes (years with a 100-year or greater flood). If **Z** has a binomial distribution with parameters **n** and **p** then its expected value and variance are:

(16) $\mu = np$

(17) $\sigma^2 = np(1-p)$

Consider, a common use of this distribution. The probability of a ten-year or greater event occurring in a year is 0.1. If we wait two years the probability of one or more of these critical events occurring is obtained by the binomial distribution function. Using the terminology contained in the "Guidelines for Determining Flood Flow Frequency" Bulletin #17B by the Hydrology Subcommittee of the Interagency Advisory Committee on Water Data, U. S. Department of the Interior this is written:

(18) $$R_I = \frac{N! \quad P^I(1-P)^{N-I}}{I!(N-I)!}$$

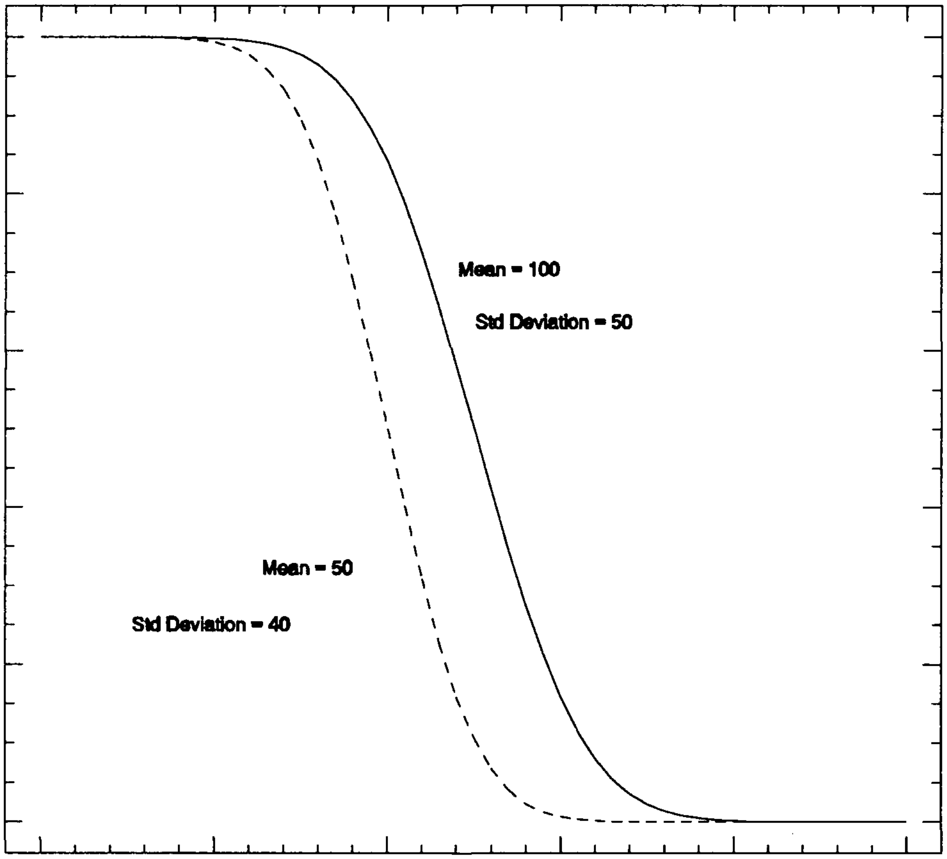

Figure D-3: Survivor Cumulative Distribution Functions--Normal Distribution

where $\mathbf{R_I}$ is the estimated risk of obtaining exactly **I** events of probability **P** occurring in **N** years. Since equation (18) provides the probability of exactly **I** events occurring. When I = 0, 0! = 1 and equation (18) reduces to:

(19) $R_0 = (1 - P)^N$

The probability of 1 or more events occurring is one minus the probability of exactly no events occurring or:

(20) $R_{(\geq 1)} = 1 - (1 - P)^N$

The computed probability for the two year period is 0.19. Probabilities of one or more critical events in a period of any length can be calculated by varying **N**.

The binomial distribution can be used in a variety of ways. Its most common use in flood protection projects is in calculating the chance of one or more events greater than the design flood

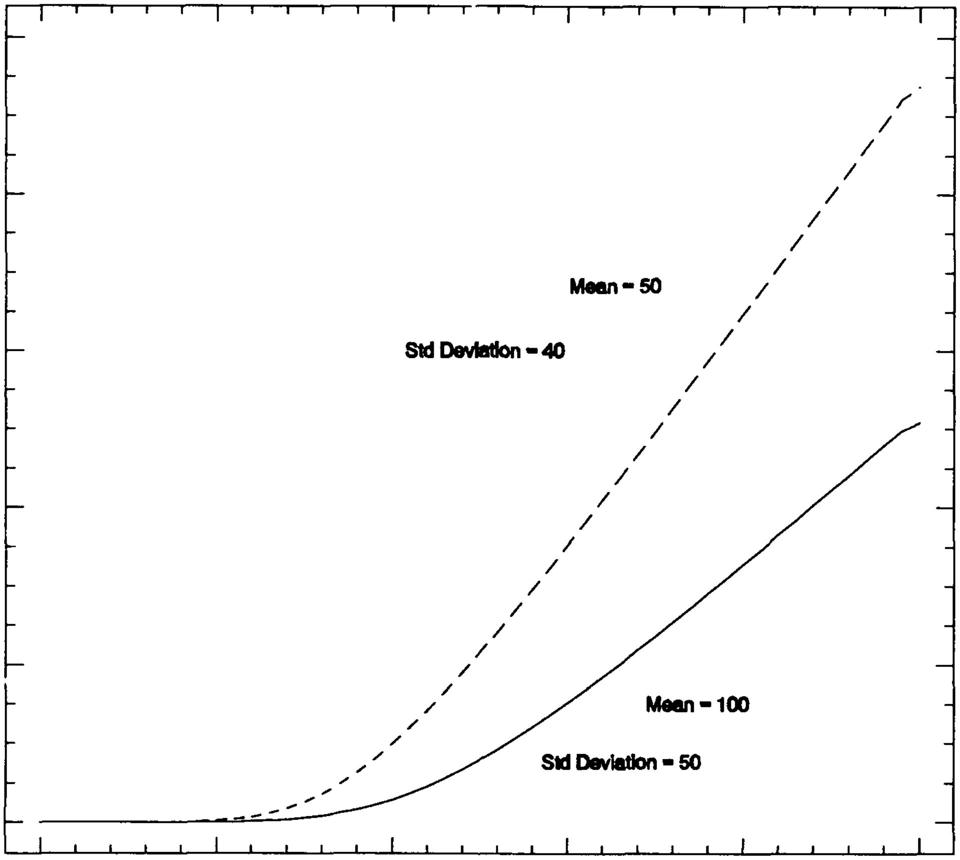

Figure D-4: Hazard Functions--Normal Distribution

occurring during the planning horizon.[10]

It can also be used to help identify an appropriate period of analysis for a Section 14 project. It is not always obvious that rip-rap bank stabilization provided by a Section 14 project will last for 50 years. For example, it is entirely feasible that some event could destroy the bank stabilization project. The exceedance frequency of that hypothetical event should be estimated in order to calculate the probability that the project will be destroyed over the period of analysis.

If the recommended rip-rap plan would be destroyed by, for example, a 50-year event, using the binomial distribution function the probability that one or more 50-year events occur over a 50-year period is 0.64. The probabilities of one or more events for 40, 30, 20, and 10 year periods are, respectively, 0.55, 0.45, 0.33, and 0.18. These data can be interpreted in terms of the expected project life, hence the period of analysis. Few people will argue that a project with

[10] For example, given that the recommended level of protection is 100-year, the probability of one or more floods of this magnitude or greater over a 100-year period is 0.63. This is obtained using equation (22) for P = 0.01 and N = 100.

Name	Range	Parameters	PDF	Expectation	Variance
Discrete Uniform	$x=1,2,\ldots N$	$N=1,2,\ldots$	$p(x) = \frac{1}{N}$	$\frac{N+1}{2}$	$\frac{N^2-1}{12}$
Bernoulli	$x=0,1$	$0 \le p \le 1$	$p(0) = 1-p$ $p(1) = p$	p	$p(1-p)$
Binomial	$x=0,1,\ldots n$	$n=1,2,\ldots$ $0 \le p \le 1$	$p(x) = \binom{n}{x} p^x(1-p)^{n-x}$	np	$np(1-p)$
Poisson	$x=0,1,\ldots\infty$	$\lambda>0$	$p(x) = \frac{\lambda^x e^{-\lambda}}{x!}$	λ	λ
Geometric	$x=1,2,\ldots\infty$	$0 \le p \le 1$	$p(x) = p(1-p)^{x-1}$	$\frac{1}{p}$	$\frac{1-p}{p^2}$
Negative Binomial	$x=r,r+1,\ldots\infty$	$r=1,2,\ldots$ $0 \le p \le 1$	$p(x) = \binom{x-1}{r-1} p^r(1-p)^{x-r}$	$\frac{r}{p}$	$\frac{r(1-p)}{p^2}$

Table D-2: Discrete Random Variable Probability Density Functions

nearly two-thirds (0.64) chance of being destroyed in 50 years has a 50-year project life. In this example it would be inappropriate to use a 50-year period of analysis. If a threshold of acceptable risk of a one-in-three chance of loss over the period of analysis for a Section 14 project is selected a 20-year period of analysis/project life would be selected. Costs would be estimated and amortized over this period. Benefits would accrue over the same period.

Selection of the period of analysis should coincide with the estimated project life. An analysis such as that presented above is intended to serve as one acceptable approach that can be used along with engineering judgment to determine the project life and to deal with some of the risk and uncertainty inherent in small projects.

FITTING DISTRIBUTIONS TO DATA

It is not always simple to select the distribution that best fits a random phenomenon. A typical first step is to collect data on a large number of independent samples of the random variable of interest. As a practical matter the acquisition of data may often be economically or physically infeasible or impossible. Analysts rarely have large quantities of data.

In the absence of a large data base, there may be a compelling theoretical reason for assuming a certain distribution is appropriate. If the phenomenon can be thought of as the sum of a large number of independent random variables, the Central Limit Theorem suggests a normal distribution is appropriate. Program Evaluation and Review Technique (PERT) and Critical Path Method (CPM) models require the use of a beta distribution. Markov processes require the use of negative exponential distributions.

Using the available data, the next step is to create a histogram. The basic shape of the frequency distribution is helpful in suggesting what distribution may best fit the data. Figure D-5 presents a histogram of the combined width of ship beams observed during 426 passing situations. Selecting one or more candidate distributions requires some familiarity with the shapes of the various PDFs.[11] It is important to know that different values for distribution parameters can lead to widely varying shapes. The analysts' goal at this point is to decide whether there is any potential for adjusting the parameters of the candidate distribution to get a PDF that looks like the histogram.

The data in Figure D-5 appear to have an approximately normal distribution. Because the normal distribution is a special case of several other more general distribution families it could also be distributed like one of these as well. Figure D-6 provides an alternative view of the fit shown in Figure D-5. As noted in above, PDFs and CDFs contain the same information. In most cases, visual comparisons of the empirical and hypothetical CDFs are easier than comparisons of the PDFs. Figures D-7 through D-9 indicate the data may have a lognormal or Weibull

[11] Derman's book is an excellent source of descriptions of the most frequently used distributions. The STATGRAPHICS software program has a distribution plotting function that, in addition to be being an excellent analytical tool, serves as a very effective learning tool. It allows the user to generate distributions by varying the parameters of 14 commonly used distributions.

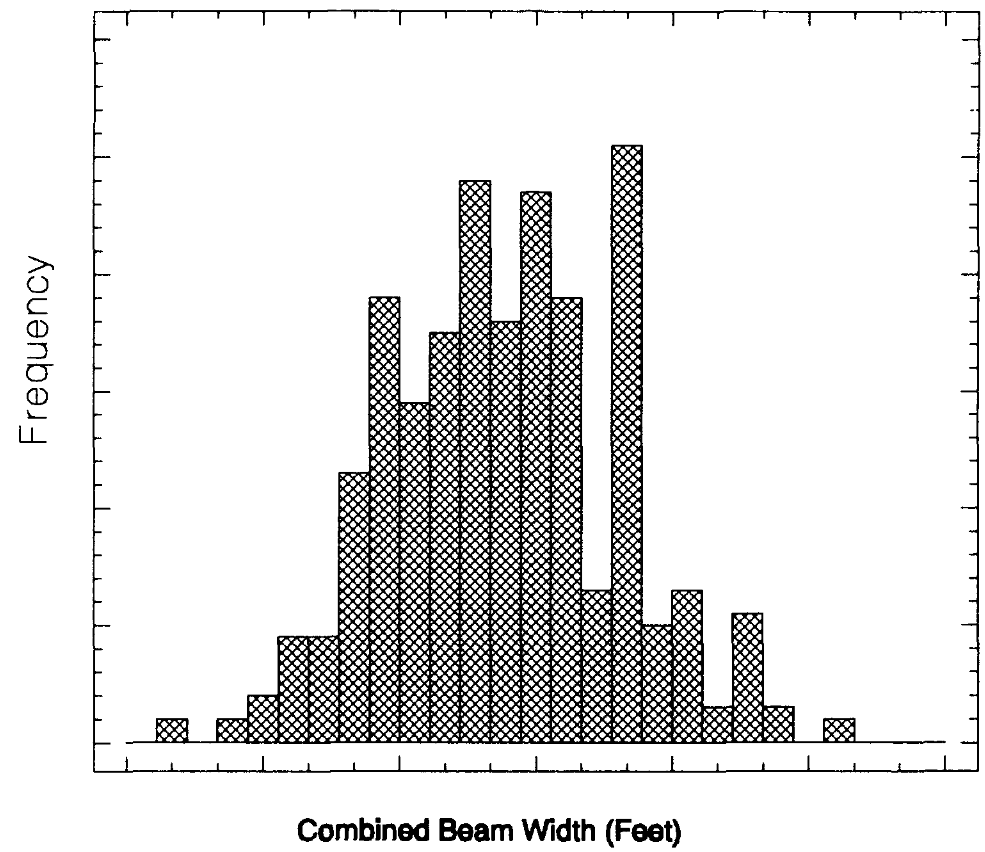

Figure D-5: Combined Beam Width Histogram

distribution as well as a normal distribution.

Once a candidate distribution is selected, analysts then determine the values of the parameters of the distribution. Once the parameters of the distribution are chosen the distribution is fixed. The values of the parameters are normally estimated statistically using the available data. For some distributions estimation of the parameters is easy. Estimates of sample means and variances can be used to estimate population means and variances. Other parameters are more complex, such as those for Gamma and Weibull distributions. Derman's (1973) book is an excellent source of information for estimating many of these parameters.

There is often a question about which set of parameter values yields the best fit. After the parameters are adjusted to yield the best fit, the question still remains - how good is the fit? The eye provides the first check. By plotting the theoretical distribution with the estimated parameters over the histogram it may be possible to judge the quality of the fit. As previously noted Figures D-6 through D-8 appear to show similar quality of fit.

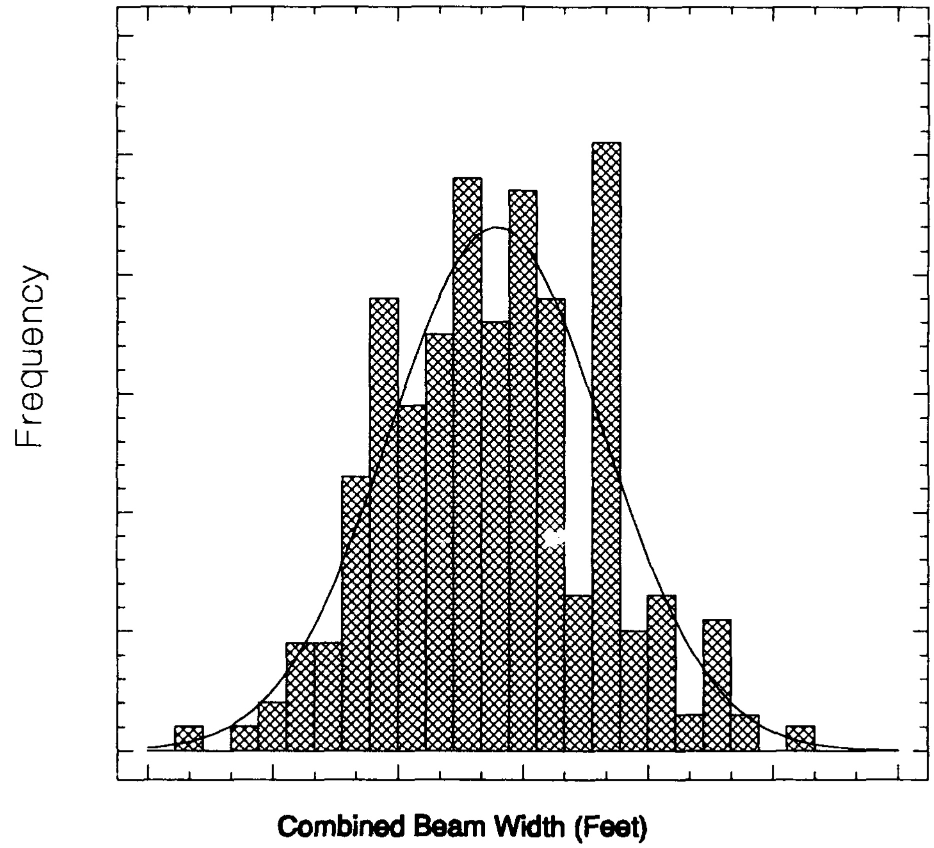

Figure D-6: Normal Distribution - Superimposed on Data

In most cases more formal tests are desired. The two most common goodness-of-fit tests are the chi-square and the Kolmogorov-Smirnov tests. The Kolmogorov-Smirnov test is usually the preferred method of the two.[12] These tests are described in most intermediate statistics texts.

[12] The Kolmogorov-Smirnov test in essence consists of a comparison of the theoretical and empirical cumulative distribution functions. The data are arrayed from lowest to highest and the theoretical distribution is plotted on top of it. The maximum absolute distance between the empirical and hypothetical distributions is used to test for conformance between the two distributions. The largest discrepancy in the two distributions are tested to see if they are in a statistical sense significantly different from one another and therefore most likely from different distributions.

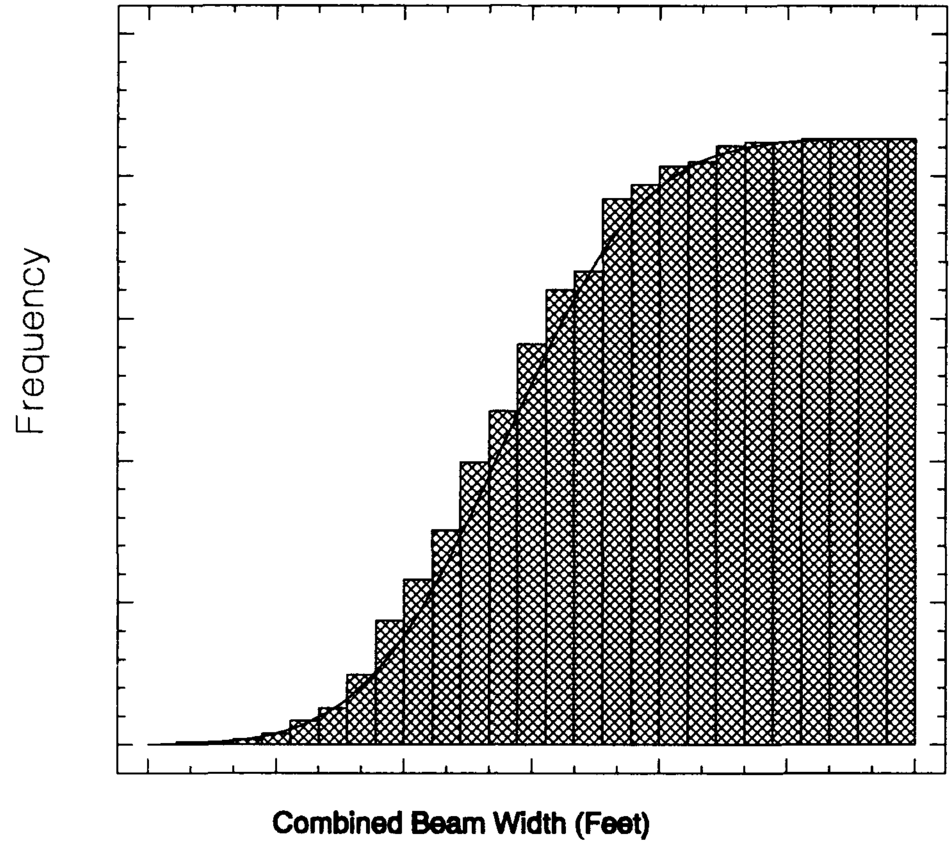

Figure D-7: Normal Cumulative Distribution - Superimposed on Data

The two tests mentioned above are based on the null hypothesis[13] that the chosen distribution is in fact the correct distribution, i.e., the observed fit is a good fit. The goodness-of-fit test leads us to reject the chosen distribution only when the discrepancies between the hypothetical and empirical distributions are large. Failure to reject the null hypothesis does not tell us if the distribution is the best fit, but only that it is a good one. So the goodness-of-fit test is by its very nature biased in favor of accepting the distribution tested.

[13] Suppose that, based on prior information (say an earlier survey by tax assessors), we had reason to believe the average value of a house in the community was $65,000. If we sample house values in the flood plain and come up with an average value of $55,000 as our estimate of $55,000 inconsistent with our prior belief that the average value was $65,000? The discrepancy between our estimate of $55,000 and our hypothesized value of $65,000 may be due to our sample size. We would not expect the average value of say three houses to be exactly $65,000!

This is a problem of hypothesis testing. We want to know if our estimates are consistent with our prior beliefs or hypotheses. The hypothesis we want to test is called the null hypothesis. It is sometimes called the prior, referring to the prior belief context above. The thing we believe to be true, based on theory, intuition, or prior information, is our null hypothesis. In the example, the null hypothesis is that the average house value is $65,000.

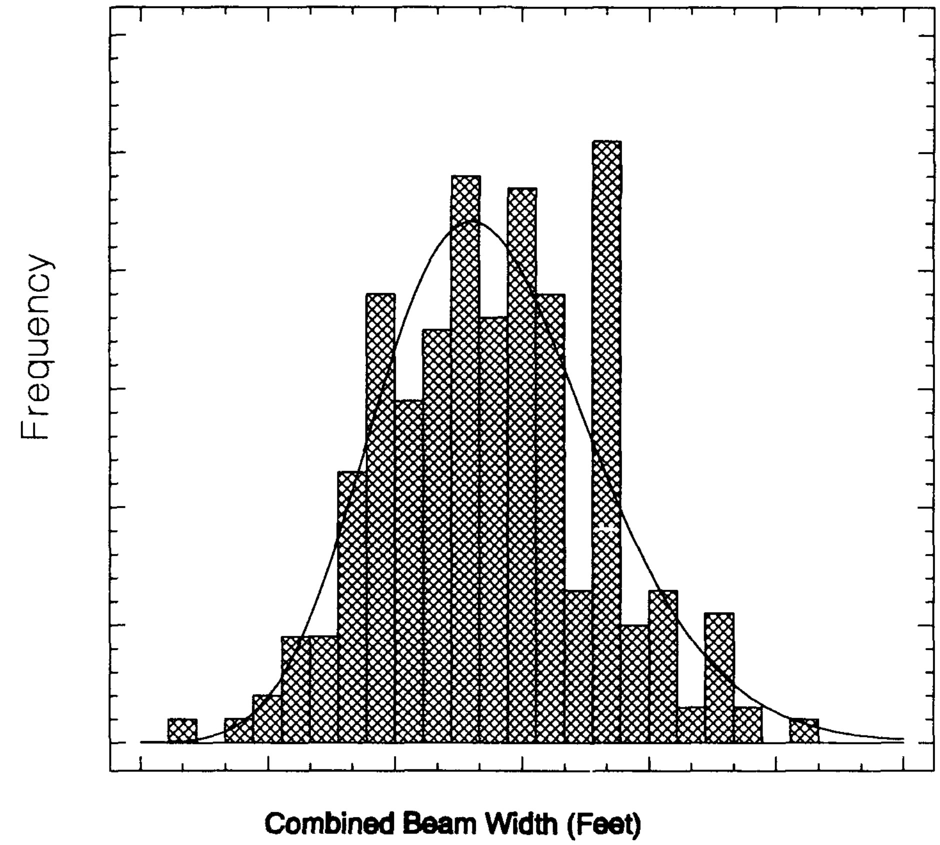

Figure D-8: Lognormal Distribution - Superimposed on Data

Table D-3 presents the Kolmogorov-Smirnov statistics for the different distributions tested. Using a 0.05 significance level[14] to reject the null hypothesis that the hypothetical distribution provides a good fit of the empirical data we can reject the hypothesis that the data have a Weibull distribution. We are not able to reject the hypotheses that the data are normal or lognormal distributed. Based on the statistical evidence the lognormal fit appears to be the best of the three.

Failure to reject the hypothesis is not always strong evidence that we have the correct distribution. The power of the statistical test is increased by the addition of data. It is well to keep in mind that no amount of data can absolutely confirm the correct distribution has been selected. On the other hand, there is no necessity for the selected distribution to perfectly model the random phenomenon of interest. It is sufficient for the distribution to represent the significant aspects of the phenomenon.

[14] Testing hypotheses is not foolproof. We could reject our null hypothesis when it is true (Type 1 error). Or, we could accept it when it is false (Type 2 error). With regard to the Type 1 error, the probability of making such an error is called the level of significance or significance level.

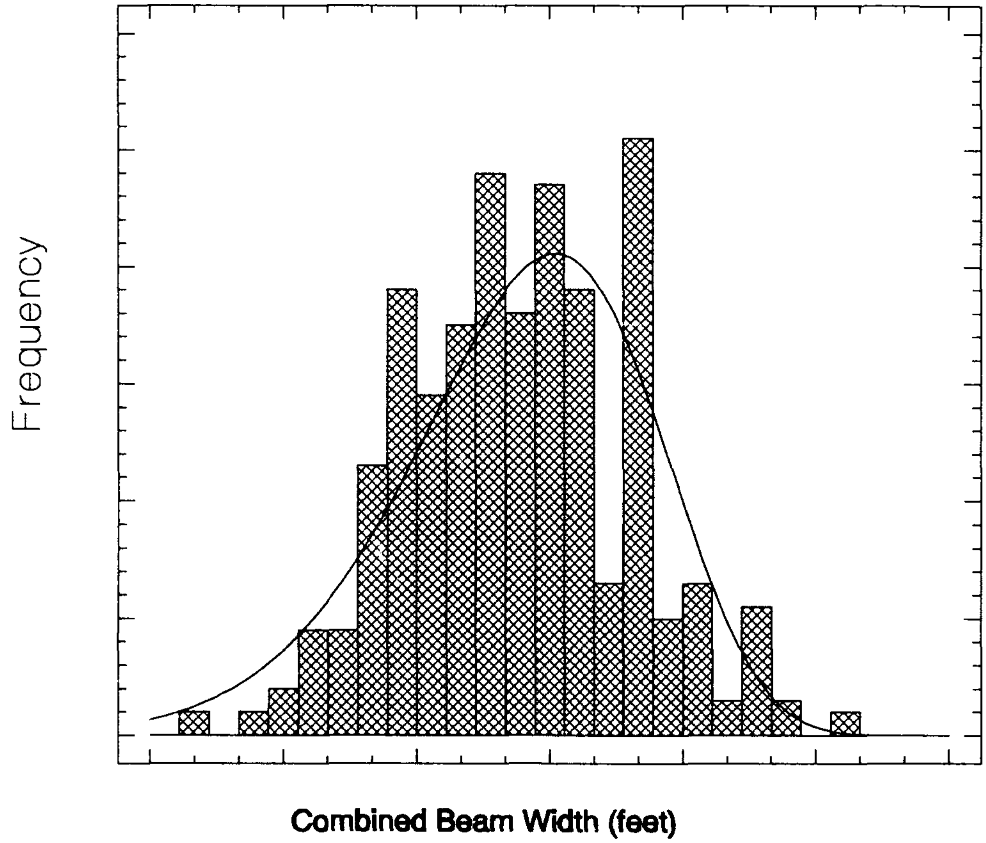

Figure D-9: Weibull Distribution - Superimposed on Data

The example indicates that more than one distribution may fit the data. The distribution used may be selected on the basis of goodness-of-fit criteria, theory, or ease of manipulation.

Distribution	K-S Statistic	Approximate Significance
Normal	0.056	0.134
Lognormal	0.053	0.172
Weibull	0.072	0.024

Table D-3: Kolmogorov-Smirnov Statistic

APPENDIX E

SAMPLING TECHNIQUES

INTRODUCTION

Each observation taken from a population contains information about the population parameter(s) of interest. Because information costs money, the analyst must decide how much information to buy. Sample size and design determine the amount of information in the data; size determining the number of samples and design controlling the variation in the sample data.

TERMINOLOGY

An element is an object to be measured. If the objective is to estimate the average value of flood plain structures, a single house is an element. The population is a collection of elements about which we want to make an inference. In our example, the population is all the houses in the flood plain. A sampling unit is a non-overlapping collection of elements from the population. Although a house is an element in the population, it may be more cost effective to sample entire blocks rather than individual homes. Sampling units may be defined as elements.

A frame is a list of sampling units. An ideal frame would include the entire population. It is not uncommon for a frame to consist of less than all elements of the population. Frames for our example may include tax records, maps, or aerial photos. A sample is a collection of sampling units drawn from a frame.

THE DESIGN OF THE SAMPLE SURVEY

The number of observations (sampling units) and the procedure to use depends on the amount of information the analyst wants to buy. If θ is the parameter we are interested in (average value of flood plain houses) and $\hat{\theta}$ is an estimator of θ the analyst should specify a bound on the error of estimation, **B**:

(1) error of estimation $\equiv |\theta - \hat{\theta}| < B$

The analyst must also specify a probability $(1 - \alpha)$ that specifies the frequency with which we require the error of estimation to be less than B in repeated samplings or:

(2) P[error of estimation $< B] = 1 - \alpha$

A typical value for $(1 - \alpha)$ is .95 for normal distributions. This corresponds to a value of 1.96 for the standard normal random variable, **z**.

SYSTEMATIC SAMPLE

A commonly used sample design is the systematic sample. If the flood plain houses are listed in the tax records it may be very economical to select one house near the beginning of the list and every tenth house thereafter. Although a convenient method, systematic sampling obtains the most information for a specified amount of money only by accident.

SIMPLE RANDOM SAMPLE

Simple random sampling consists of selecting a group of **n** sampling units from a population of size **N** in such a way that each possible sample of size **n** has the same chance of being selected. Using one's judgment to "randomly" select the sample is haphazard sampling. "Choosing" a representative sample is as subject to analyst bias as haphazard sampling. The properties of estimators from such samples cannot be estimated.

A simple random sample can be selected using a table of random numbers, a random number generator, lottery, or similar random method. Choosing numbers from a table of random numbers is similar to drawing numbers from a hat. To draw a sample of 100 houses from a population of 1,000 we could put the addresses of each house in a hat and draw the sample one at a time. Each slip is replaced after selection to insure that every house has an equal probability of being selected in each draw. If an address is drawn a second time it is simply replaced and a new one is drawn.

Analogously, we could drop a pencil point on a table of random numbers to establish a random starting point. Suppose the pencil falls on the 21^{st} line of column 4 and we decide to use the four digits on the left of the random number. Each house in the frame would be numbered from 1 to 1,000. The house with a number corresponding to that in the table is selected for the sample. We can now proceed in any direction (up the column, down the column, across the page, etc.) to select the remainder of the sample. A random number generator effectively determines the path of numbers described above. Once a sample is drawn, it is possible to estimate the parameter(s) of interest, their confidence intervals, and so on.

A critical issue in designing the sample is to estimate the sample size required to estimate the parameter with the desired error bound, **B**. To estimate the sample size, **n**, needed to estimate a mean we can use:

(3) $n = (N\sigma^2)/((N - 1)D^2 + \sigma^2)$

where $D = B^2/z^2$.

Where **N** is the population size and **B** is as previously stated. Solving equation (3) for **n** is not often easy because the population variance σ^2 is not known. A sample variance S^2 may be available from earlier work, a smaller sample, etc. S^2 can be used to replace σ^2 in the equation. If the sample variance is not known an approximation can be obtained from the knowledge that the range is approximately equal to plus or minus four standard deviations ($\pm 4\sigma$). Thus if the range of values can be approximated, one eighth of the range can be used as an estimate of σ.

If the homes in our flood plain range in value from \$20,000 to \$100,000, are measured in thousands, i.e., \$20 to \$100, and we want $B \leq \$5$, we find N = 1,000, D = 6.25 and σ can be estimated by one eighth of the range (\$80) or \$10. Using equation (3) we find:

n = (1000(102))/(999*6.25) + 10^2
n = 15.76 say 16

The formula for determining the sample size for a given error bound varies with the parameter to be estimated and the sample design.[1]

STRATIFIED RANDOM SAMPLE

A stratified random sample may increase the information available from a sample at a given cost. A stratified random sample is obtained by separating the population elements into nonoverlapping groups, called strata, and then selecting a simple random sample from each stratum. In our example, the analyst may want to separate the houses to be sampled according to elevation or flood plain. The strata may consist of 10-year, 10-year to 50-year, and greater than 50-year flood plains. Alternatively, the analyst may find it helpful to group the structures by relative size, value or age before sampling.[2]

The first step is to clearly identify the strata. Following strata identification, next place each sampling unit of the population into the appropriate stratum. After the population is stratified a simple random sample is drawn from each strata. The formulas for estimating the necessary sample size becomes correspondingly more complex than that for the simple random sample.[3]

CLUSTER SAMPLE

A cluster sample is a simple random sample in which each sampling unit is a collection or cluster of elements. If a list of houses in the flood plain is not available via tax records, maps, or photos, it may be more cost effective to develop a sample based on blocks. The first task is to specify the cluster. Because elements within a cluster tend to be very similar to each other there is no advantage to having a very large cluster. Little new information is gained from the additional elements in the cluster. Once the clusters have been specified a frame is constructed and a simple random sample of clusters is selected from the frame.

Cluster sampling can be conducted within a stratified population to further increase information per dollar of cost. Two-stage cluster sampling consists of selecting a simple random sample of clusters and then selecting a simple random sample of elements from each sampled cluster.

[1] For example, population means and population proportions have different formulas as do simple random samples and stratified random samples.

[2] The strata can be as simple (flood plain) or as complex (flood plain, square footage, value, age, etc.) as desired.

[3] The text by Scheaffer, Mendenhall, and Ott (1979) provides a very accessible introduction to survey sampling and the basic formulas needed. The book includes a number of excellent examples to illustrate the use of the various techniques.

APPENDIX F

EXPECTED UTILITY THEORY

INTRODUCTION

Utility is a scale of measurement of the satisfaction derived from some economic good, particularly income or wealth. In situations of risk and uncertainty, expected utility may be a truer measure of worth than expected monetary values. This appendix addresses how expected utility theory can apply to decision-making under such conditions.

The starting place for this discussion of the currently most popular theory[1] of risk-bearing is an analysis of a choice in which no risk is present. Decisions made in such a safe world are trivially simple if we assume that outcomes can be measured in money terms.

Consider a flood that will occur at a known future date that will cause $1 million in present value damages. Given the choice of doing nothing, with a present value payoff of -$1 million dollars, or spending $0.5 million dollars present value for protection that will eliminate all damages the choice between alternatives is simple. Flood protection costs $0.5 million while doing nothing costs twice as much. Assuming utility increases with income and we are utility maximizers, we would clearly choose flood protection over doing nothing.

Most of our choices are not made under conditions of certainty. Many of them cannot be measured in money terms. For the remainder of this appendix we will be concerned only with risky choices (or uncertain choices whose outcomes can be expressed in terms of their subjective probabilities) and those choices that can be measured in money terms.

CLASSICAL PERSPECTIVE

The expected utility model was initially proposed as an alternative to an earlier more restrictive theory of risk-bearing. During the development of modern probability theory it was assumed by 17th century mathematicians Blaise Pascal and Pierre de Fermat that the value of a risky proposition was given by its expected value. Expected value is the product of the monetary value of an outcome and the probability of the outcome being realized. Choices were based on the alternative that yielded the highest expected value.

The expected value theory of risk-taking prevailed until it became generally recognized that people consider more than just expected value in risk-bearing decisions. This point was dramatically illustrated by Nicholas Bernoulli's example in 1728 known as the St. Petersburg Paradox:

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[1] Economic theory of choice under uncertainty, once thought to have been settled by expected utility theory, is once again unsettled. There is a growing mass of evidence that suggests individuals do not always maximize expected utility. Machina (1989) provides an excellent review and bibliography of this evidence.

Suppose someone offers to toss a fair coin repeatedly until it comes up heads, and to pay you \$2 if this happens on the first toss, \$4 if it takes two tosses to land a head, \$8 if it takes three tosses, \$16 if it takes four tosses, etc. What would you be willing to pay for a single play of this game?

The expected value of this game is:

$$(1)\quad \Sigma\, p_i x_i = (.5)2 + (.5)^2 2^2 + \dots + (.5)^n 2^n$$
$$= 1 + 1 + \dots + 1 + \dots$$
$$= \infty$$

With an expected value of $\$\infty$ this game clearly has infinite value. A person following the expected value theory of risk-bearing would prefer this game to any finite sure gain, i.e., he should be willing to pay any finite price to play the game because the expected payoff is infinite.

In fact, few individuals would pay more than a few dollars to play this game. What causes the expected value rule to fail in this simple paradox? The answer is that people consider more than expected value. The expected value rule ignores risk attitudes, a factor for most people.

Daniel Bernoulli suggested that this problem could be solved by assigning weights to the money outcomes yielded by expected value computations.[2] This idea was refined over time and has evolved into what is now termed a von Neumann-Morgenstern utility function $U(\cdot)$. Rather than using expected value, $\Sigma x_i p_i$, most people evaluate risk-bearing situations on the basis of expected utility, $\Sigma U(x_i)p_i$.

EXPECTED UTILITY MODEL

To see the connection between utility and risk consider a simple gamble. The choices are (1) to keep our current wealth of \$10, or (2) to enter a fair gamble at a cost of \$10 with a .5 chance of winning \$10 and a 0.5 chance of winning \$0.[3] In terms of our wealth, the gamble means a 0.5 chance of wealth = \$0 and a 0.5 chance of wealth = \$20.

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[2] Let's reconsider the St. Petersburg's Paradox allowing an individual to associate different levels of utility with different amounts of income. To make the point simply let the total utility of income be related to the amount of income by the function $U = x^{0.5}$. Thus, x = \$500 for the individual with this utility function receives 22.36 units of utility. That same person would get only 5.92 extra units of utility from an additional \$300, but would lose 8.22 units of utility by a loss of \$300. While the expected monetary value of the paradox is infinite its expected utility (EU) is:

$$EU = (1(.5))^{0.5} + (2(.5)^2)^{0.5} + (4(.5)^3)^{0.5} + \dots = 1.707 \text{ units of utility}$$

Because $U = x^{0.5}$, $U^2 = x$ so the dollar equivalent of this utility is \$2.91. This is a far cry from the earlier expected value.

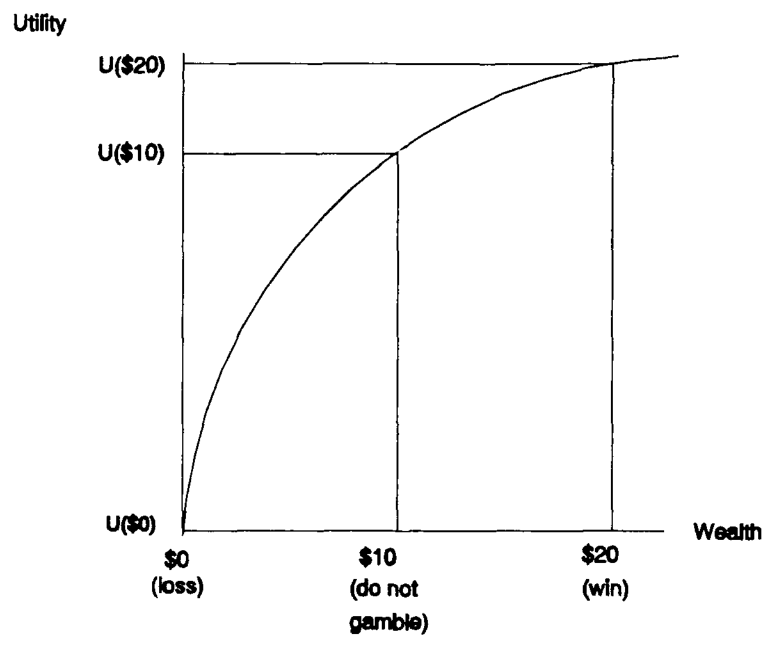
[3] Fair gambles or fair games are those that have an expected value of zero. In the example, there is a .5 chance of gaining \$10 and a .5 chance of losing the \$10 cost of the gamble.

Figure F-1 shows a utility function that conforms to the Von Neumann-Morgenstern utility function.[4] If the gamble is not taken, wealth equals $10 and this has a utility value of U(10) as shown on the vertical axis. Taking the gamble and losing reduces wealth to $0. This has a utility of U(0). Winning results in wealth of $20 with a utility of U(20).

Notice that the gain in wealth of $10 from winning results in a much smaller change in utility U than does a loss of wealth of $10, when compared to the initial U(10). The distance U(10) - U(0) is much greater than the distance U(20) - U(10).

If the utility function is of the form shown, a gamble represents a trade in which the individual is sacrificing highly valued dollars (associated with low levels of wealth) for a chance at winning lesser valued dollars (associated with higher levels of wealth). This function exhibits diminishing marginal utility. Diminishing marginal utility of wealth conveys the notion that utility does not increase as rapidly as wealth may. It suggests that losing a unit of wealth is of greater consequence to a person than is gaining an equivalent unit of wealth. The diminishing marginal utility of wealth/income creates a bias against gambling.

Figure F-1: Von Neumann - Morgenstern Utility Function for a Fair Gamble



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[4] For a rigorous description of the mathematical properties of such a utility function see John von Neumann and Oskar Morgenstern's Theory of Games and Economic Behavior. More accessible descriptions of the function are available in economics texts like that of Henderson and Quandt.

The relationship between utility and risk can now be examined more carefully. The expected utility rule represents a revised decision rule that substitutes utility values for money values in risky situations in order to select from among risky alternatives. The utility values are generally based on an individual's wealth. The rule is based on a set of axioms that will not be considered here (see footnote 4).

An expected utility, EU, is assigned to a risky alternative as follows:

(2) $EU = \Sigma\, p_i U(x_i)$

where
EU = expected utility of the alternative,
p_i = probability of outcome x_i, and
$U(x_i)$ = utility value of outcome x_i derived from the individual's utility function.

There is a clear symmetry with the expected value rule. Expected value is the weighted average of monetary outcomes and expected utility is the weighted average of those same outcomes after they have been expressed in utility values.

The application of the expected utility rule is best illustrated with a bit more detail. Suppose an individual has the option of receiving \$10 with certainty and a gamble with a 0.5 probability of winning \$20 and 0.5 probability of winning nothing (\$0). In Figure F-2, the utility of winning and losing a gamble are shown as U(\$20) and U(\$0), respectively, on the vertical axis. Given 50-50 odds, the average of these two utility values is given by the midway point between U(\$20) and U(\$0). In more formal terms, the expected utility of the gamble, EU_g, is:

(3) $EU_g = 0.5U(\$20) + 0.5U(\$0)$

The alternative is, of course, not to gamble. The expected utility of not gambling, EU_{ng}, is:

(4) $EU_{ng} = 1.0U(\$10) = U(\$10)$

Not gambling means a wealth of \$10 for certain. EU_{ng} is also shown on the vertical axis.

The curved function in Figure F-2 represents the utility function. The straight line function represents the expected utility function. It indicates that for the two payoffs, the expected utility increases as the probability of winning increases.

The utility from taking the \$10 with certainty (not gambling) is clearly higher than that from gambling, as the utility from a sure \$10 is greater than the utility of an average of \$10. Considering expected utilities, the expected utility of a certain \$10 (EU_{ng}) is greater than the utility from an expected value of \$10 (U(E\$10)). This result should not be construed to mean that the individual depicted in Figure F-2 should never gamble. This result simply means that at the given cost of the gamble, payoff, and odds; the individual will not gamble.

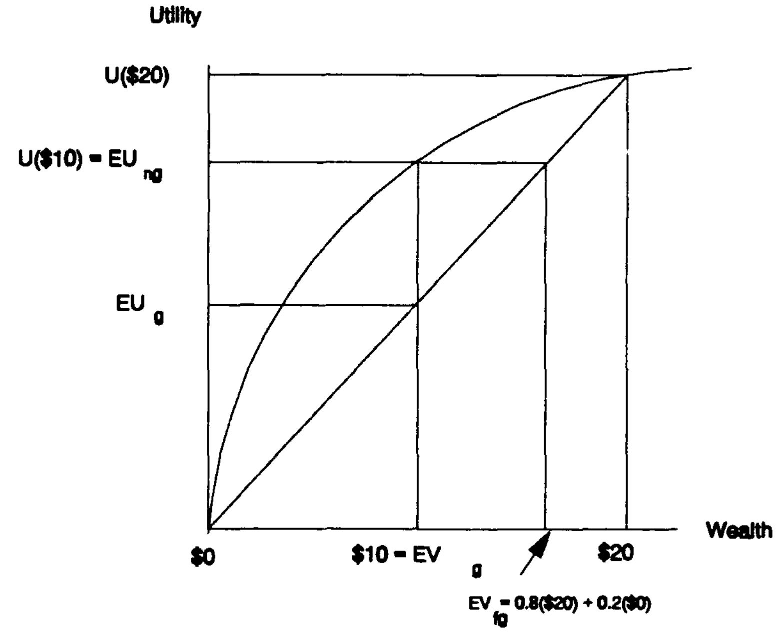

Figure F-2: Expected Utility Example

The odds can be adjusted until we arrive at a gamble that is just acceptable for this individual. The expected value of the above gamble was 0.5($0) + 0.5($20), or $10. If the odds of winning are 0.8 the expected value becomes 0.1($0) + 0.8($20), or $16. The decision rule is of course based on expected utility, not expected value, and the expected utility of the more favorable gamble, EU_{fg}, is:

(5) $EU_{fg} = 0.8U(\$20) + 0.2U(\$0)$

In this case, the gamble yields the same expected utility as the no gamble option (i.e., $EU_{fg} = EU_{ng}$). This individual is now indifferent between receiving $10 with certainty and a gamble with 0.8 probability of winning $20 and 0.2 probability of winning $0.

If an individual has a concave utility function of the form shown here, the individual is risk averse by definition. This is based on the general statements we can make from the analysis presented above.

1) The individual would not rationally gamble at fair odds.
2) The odds would have to be loaded in the individuals favor in order to induce him or her to gamble.

Aversion to risk implies a willingness to pay to avoid risk, a point to be taken up in the next section. It is worth noting that an individual with a convex utility function derives positive value from risk and would gamble at worse than fair odds.[5] Such people are considered to exhibit risk preferring or risk seeking behavior.

Risk neutral individuals have linear utility functions and consider only the expected values of alternatives. They are indifferent to the odds of the gamble.

Figure F-3 illustrates typical utility functions for risk neutral, risk averse and risk seeking individuals.

FLOOD CONTROL AND THE EXPECTED UTILITY RULE

The gamble presented in the preceding section aids the presentation of some basic points about expected utility and risk averse behavior. A gamble entails the sacrifice of certain wealth to acquire an opportunity to increase one's wealth. Navigation projects may be modeled by such a situation, the money paid being project costs and the increase in wealth being the realization of project benefits.

In this section the concept of risk costs or a risk premium is illustrated in the context of a flood control project. The purpose of the presentation is to develop the expected utility theory more fully and to apply it to a water resource setting. The result will show that if people are risk averse, expected annual damages understate willingness to pay for flood control and may be a low estimate of project benefits.

Assume your wealth is \$120,000, of which \$100,000 is the value of your home. Suppose you live in the flood plain. Your house may or may not be flooded, but if it is, assume it to be a total loss. Thus, a flood reduces your wealth to \$20,000. You are considering a ring levee that would completely protect your house.[6] What is the value of flood protection to you, i.e., what are you willing to pay for flood protection?

Suppose we know the annual probability of a flood is 0.25.[7] Since your final wealth will be either \$120,000 with no flood or \$20,000 with a flood, with respective probabilities of 0.75 and 0.25, your expected utility with no levee, EU_{nl}, is:

(6) $EU_{nl} = 0.75U(\$120{,}000) + 0.25U(\$20{,}000)$

The expected value of the loss is 0.25(\$100,000) or \$25,000. This is a measure of the expected annual flood damages in this simple example. The expected value of your wealth is thus \$95,000.

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[5] A convex function slopes up at an increasing rate rather than a decreasing rate.

[6] To assist in focusing on the concept of risk cost, assume the levee provides 100 percent certain protection from flooding.

[7] The numbers used in this example are chosen for the ease of computation.

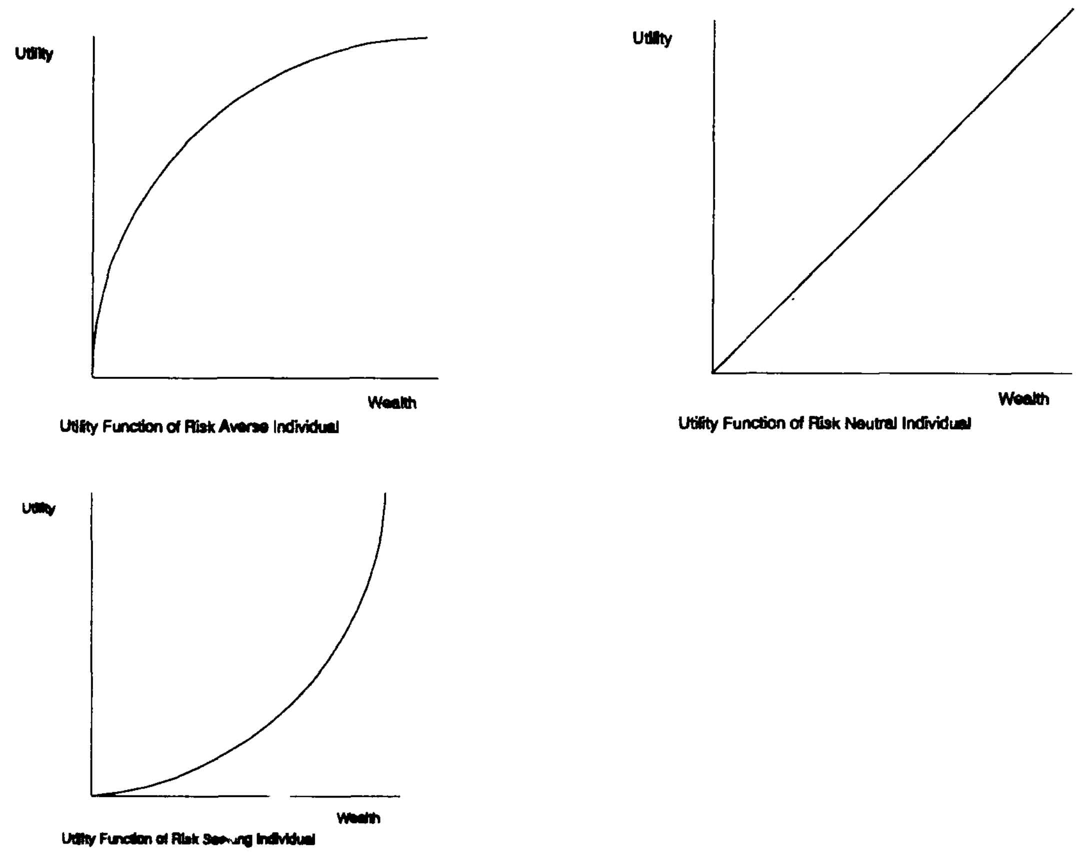

Figure F-3: Risk Attitudes and Utility Functions

Consider Figure F-4, showing a risk averse utility function, for this flood example. The horizontal axis shows possible values of terminal wealth. The amounts \$20,000 and \$120,000 represent wealth positions if you do not build the levee. The respective utility positions are shown on the vertical axis.

A levee at a cost of \$25,000 will eliminate the loss associated with a flood, but you must sacrifice \$25,000 of certain wealth to build it. If you build the levee your wealth position will be \$95,000 with a probability of one. The expected utility for the alternative of building a levee, EU_l, is:

(7) $EU_l = 1.0U(\$95,000) = U(\$95,000)$

Figure F-4 shows both EU_{nl} and EU_l on the vertical axis. EU_{nl} is 0.75 of the distance from U(\$20,000) to U(\$120,000), based on the probability weights used. As shown, EU_l is greater than EU_{nl}. This suggests that the levee should be built. This is not a chance result. It means that the utility derived from \$95,000 with certainty exceeds the utility of an uncertain situation (flood or

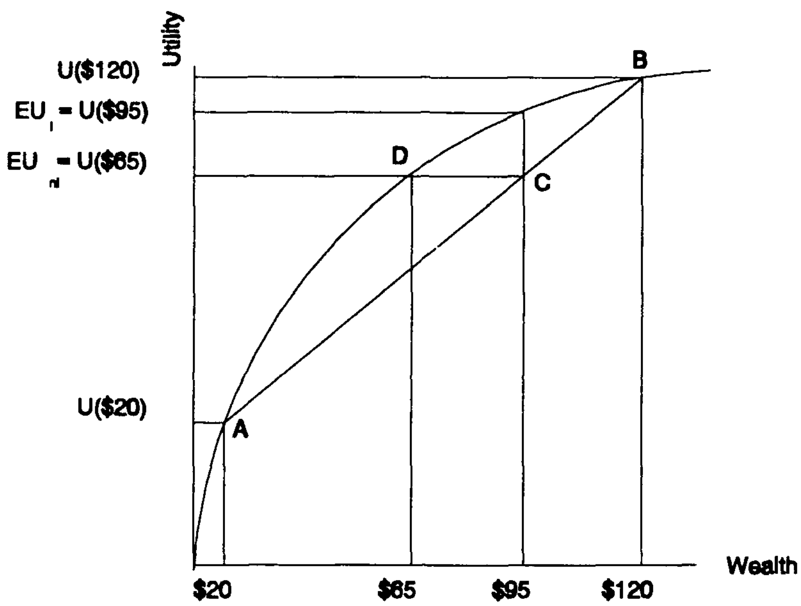

Figure F-4: Expected Utility Example for a Flood Protection Project

no flood) with an expected value of $95,000. A risk averse person prefers a sure thing to a risky venture.

The line AB connects the two alternative wealth positions without the levee. The line contains all expected values of wealth that are possible. The point C is determined by the probabilities in this example. Note that the projection of point C onto the vertical axis also intersects the utility function at point D. Projecting from D to the horizontal axis we identify the point $65,000. This means that EU_{nl}, as defined above, is equal to U($65,000).

This is an important point. It tells us that utility with $65,000 for sure is exactly the same as utility from a risky proposition with an expected wealth of $95,000. That is a non-trivial difference of $30,000. It has an interesting interpretation in the context of our flood control example.

The flood situation in which you find yourself results in an expected wealth of $95,000 for you. This is an expected value, however, a weighted average that reflects the fact that your true wealth will be either $20,000 or $120,000. The result we are now considering tells us that you would be just as happy (same utility) with a certain wealth of $65,000[8] as you would be with a 0.75 chance of $120,000 and 0.25 chance of $20,000.

Expected damages are $25,000. Expected damages are used as a proxy measure of an individual's willingness to pay for flood control. Willingness to pay, of course, being the basis of flood control benefits. Yet we have just seen a risk averse individual willing to pay more than the value of expected annual damages, in this case $30,000 rather than $25,000.[9] This $5,000 excess is a premium the individual is willing to pay to have a certain amount of wealth that leaves her as well off as the expected wealth that results from the risky situation. If flood plain occupants are risk averse, they may well be willing to pay a premium beyond their expected losses to rid themselves of the risk. To the extent this is true, expected annual damages underestimate willingness to pay for flood control, hence they underestimate flood control benefits.

This risk cost or risk premium may be defined as the maximum reduction of the expected value of wealth that an individual would accept to obtain a given wealth that is certain rather than chancing a risky expected wealth. Alternatively stated, risk cost is the minimum amount of money that an individual should receive as compensation for taking a risk.

CALCULATING PERSONAL UTILITY

The expected utility rule is a very useful device for helping us to think about risky decisions. It is generally expected that individuals will not be indifferent to uncertainty. Uncertain returns are not valued at their expected values by risk averse or risk preferring individuals.[10] The rule focuses attention on the types of tradeoffs that have to be made.

One problem with the expected utility method is that it requires us to make assumptions about an individual's risk preferences and hence the shape of their utility function. Empirical analysis requires us to know the precise form and shape of the individual's utility function. In this section, a method is presented to illustrate the feasibility of calculating a personal utility curve.[11] Although this method is more often used in the context of an individual making

[8] The $65,000 is also known as the certainty equivalent income. That is, it is the minimum amount of certain income that yields the same utility as the expected income.

[9] That people are indeed willing to pay more than the expected value of their losses in many risky situations is the very basis for the insurance industry. Premiums paid by the insured must cover the expected damages with enough left over to finance the insurance industry.

[10] This appendix focuses exclusively on risk averse behavior. For a more complete treatment of the topic including risk preferring and risk neutral behavior see Neil Doherty's Corporate Risk Management, 1985, or any number of advanced economics texts.

[11] The method used has been widely discussed in the economic and psychological choice literature. For one of the most accessible descriptions of the method see the text by Teweles, Harlow and Stone, 1987.

personal choices, it is adapted here to the case of a decision maker making program decisions.[12] The participant is asked to place herself in the role of "investment manager" for the inland waterways system. Using available data, we identify the largest dollar gains possible from system reinvestment as $2 million. We also know the largest dollar losses that will result from no reinvestment are $400,000[13]. The precise value of these extremes is less important than that they bracket the range of feasible values appropriately.

To construct the utility curve, we first define the utility of a $2 million gain as U = 1 and the utility of a $.4 million loss as U = 0. At this point, we ask the key person, "Would you make an investment offering a gain of $2 million with a probability of 0.9 and a loss of $.4 million with a probability of 0.1?" If she answers yes, we then ask, "Would you pay $1 million for this investment opportunity?" If she answers yes, again we come back with, "Would you pay $1.1 million?" "Yes." "Would you pay $1.2 million?" "I'm not sure." "Would you pay $1.3 million?" "No."

By this iterative questioning process, we establish the maximum amount the manager would pay for the uncertain investment opportunity. The process continues, varying the probabilities of a $2 million gain and a $.4 million loss each time. Table F-1 displays the results for this example.

At some point during the process we may reach the point where the choice becomes so unattractive that the decision maker is not willing to pay any price for the investment. At this point we begin to ask if the decision maker would undertake the investment if she is given $.1 million. If not, we raise the amount again and again until we get a "not sure" answer that allows us to pinpoint the minimum amount she would accept to undertake the investment. These values are reflected as negative amounts in the last column. The "Best Result" column is the probability of gaining $2 million. The "Worst Result" column is the probability of losing $.4 million. "Computed Utility" is the expected utility obtained by:

(7) $p_b(1.0) + p_w(0.0)$

where p_b is the probability of the best result, earlier defined as 1.0 on the utility scale, and p_w is the probability of the worst result, defined as $U = 0$.

Figure F-5 shows the hypothetical utility curve for our decision maker. We can obtain as many points as we want by manipulating the probabilities of gain and loss and the amount to be paid for the investment.

---

[12] The example is purely hypothetical. The numbers used are chosen for the ease of exposition rather than their realistic qualities.

[13] The values in Table F-1 are based on PMS data for Lock and Dam 20 on the Mississippi River. Average delay in hours from 1977 to 1986 was 6,006 hours annually. Using the average hourly cost of a 10,000 HP tow of $663 per hour this mean delay costs $4 million per year. For argument's sake assume a reinvestment program can eliminate half of the delay, then the maximum payoff for reinvestment is $2 million. If there is no reinvestment assume a 10 percent increase in delay costs. This fixes the maximum loss at $.4 million.

Table F-1: Hypothetical Computation of Personal Utility for a Decision Maker

Best Result	Worst Result	Computed Utility	Dollar Equivalent
1.0	0.0	1.0	$2,000,000
0.9	0.1	0.9	1,200,000
0.8	0.2	0.8	950,000
0.7	0.3	0.7	750,000
0.6	0.4	0.6	550,000
0.5	0.5	0.5	400,000
0.4	0.6	0.4	50,000
0.3	0.7	0.3	(100,000)
0.2	0.8	0.2	(300,000)
0.1	0.9	0.1	(350,000)
0.0	1.0	0.0	(400,000)

The shape of the curve reveals information about the respondents' risk preferences. A concave curve indicates risk averse behavior, a convex curve risk preferring. Linear segments indicate risk neutrality. A utility curve may show evidence of more than one kind of behavior. It is well established in the literature that it is reasonable for people to exhibit different types of behavior over different ranges of wealth, or in this case returns to investment. This method can be used on individuals to establish whether they are in fact risk averse.

Given the upper and lower bound on the benefits for any project, this approach, applied to decision makers, can be used to estimate a certainty equivalent level of benefits to compare to the expected value of benefits.[14]

ALTERNATIVES TO EXPECTED UTILITY

The expected utility rule is not without its problems. One of the most pragmatic problems is that utility functions are not available. Even where this problem is sidestepped there are

[14] In the previous section a certain income of $65,000 (analogous to certainty level of benefits) was equivalent to an expected income of $95,000 (analogous to the expected value of benefits).

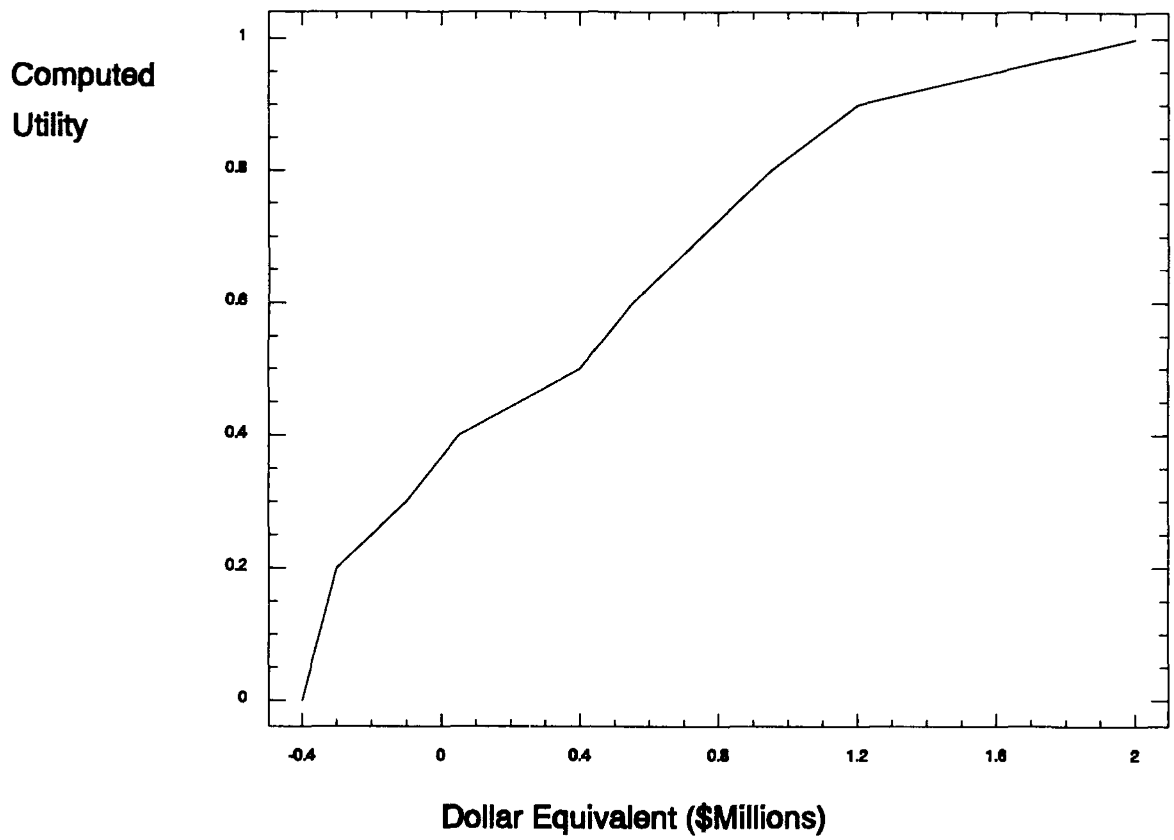

Figure F-5: Hypothetical Personal Utility Curve

substantial problems with the theory that raise questions about its applicability.[15] There are a number of alternatives to expected utility, each generally proposed to address one or more of the weaknesses of the theory. What is most useful to practitioners is an alternative that is not more complex than expected utility theory. Two such alternatives are the mean variance rule and stochastic dominance.

Mean Variance Rule

In most real-life situations, expected value has limitations as a decision rule because it ignores risk. Where expected utility theory depends on a subtle and indirect treatment of risk, the

[15] Mark Machina has an excellent introductory article to the nature of some of these problems in Vol. 1 No. 1, 1987, of the Journal of Economic Perspectives. He discusses non-expected utility alternatives in his 1989 Journal of Economic Literature article.

mean variance approach finds a direct measure of risk so that both expected value and risk can be used in the decision process.

Consider the alternatives in Table F-2. If people are risk averse and maximize the expected value in this case, we find that A is better than B, C, or D; C is better than B; and D is better than B. Notice that this risk/expected value rule does not rank all alternatives. In the above pairwise comparisons, the preferred alternative is always better on at least one of the criteria and it is never worse in the other. The pair of choices C and D cannot be ranked. Alternative D is better on the risk criterion, but C yields a higher expected value.

To make this approach work we need to measure the characteristics. The mean is, of course, just the usual expected value. Although many measures of risk are available one of the most convenient is the variance. The greater the variance, the higher the risk. Thus, all we need do is estimate the mean and variance of each alternative, enter the values in a table like that above, and compare. Unfortunately, even with numerical values, the problem of incomparable pairs remains.

An additional problem is introduced when considering variance. Given that net benefits of one project have a variance of $500, while the variance of another has net benefits of $1,000, it would appear that the second of these is the riskiest. However, if the mean of the first project is $1,000 and the second $1,000,000 the situation is changed. Clearly, the variance in possible outcomes is relative to the size of the mean outcome.

Figure F-6 illustrates graphically the trade-offs of the alternatives of Table F-2. Because net benefits for any alternative is a random variable, it will have a distribution.[16] These figures can represent alternatives with different distributions of net benefits. The narrower the distribution the less risky. High expected values are located farther to the right on the real number line.

To make our mean variance measure of risk a relative one, use the coefficient of variation:

(8) $v = \sigma / \mu$

where **v** is one simple measure of relative risk. High values of **v** indicate relatively more risky projects.

Stochastic Dominance

Stochastic dominance is a set of decision rules that is applied progressively to more restrictive groups of alternatives. Anything more than an intuitive understanding of this method is well beyond the scope of the Guidelines and Procedures.

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[16] Net benefits for a given project will have different net benefits if we use different values for: Manning's **n** in the H & H work, mean structure value, unit costs for any materials or labor, etc. Although the manner in which results are presented often implies certainty and precision, they in fact possess neither.

Table F-2: Example Alternatives - Mean Variance Rule

Alternative	Risk	Expected Value
A	Low	High
B	High	Low
C	High	High
D	Low	Low

The distributions of alternatives A and D are shown together on Figure F-7. Figure F-8 shows the cumulative distributions of these same alternatives.[17] The preference for the high net benefit, low risk alternative (A) over the low net benefit, low risk alternative (D) is clear in each figures. Both distributions have the same shape indicating the same level of risk, but the preferred alternative clearly centers around a higher level of net benefits.

This reveals the first rule for stochastic dominance:[18]

> If the cumulative distribution of A is equal to, or below that for D, for every level of wealth, then prospect A dominates (is preferred to) prospect D.

[17] Cumulative probability distributions shows the probability that any given outcome will be equal or less than a given value.

[18] Doherty, Neil, Corporate Risk Management (1985), p. 67.

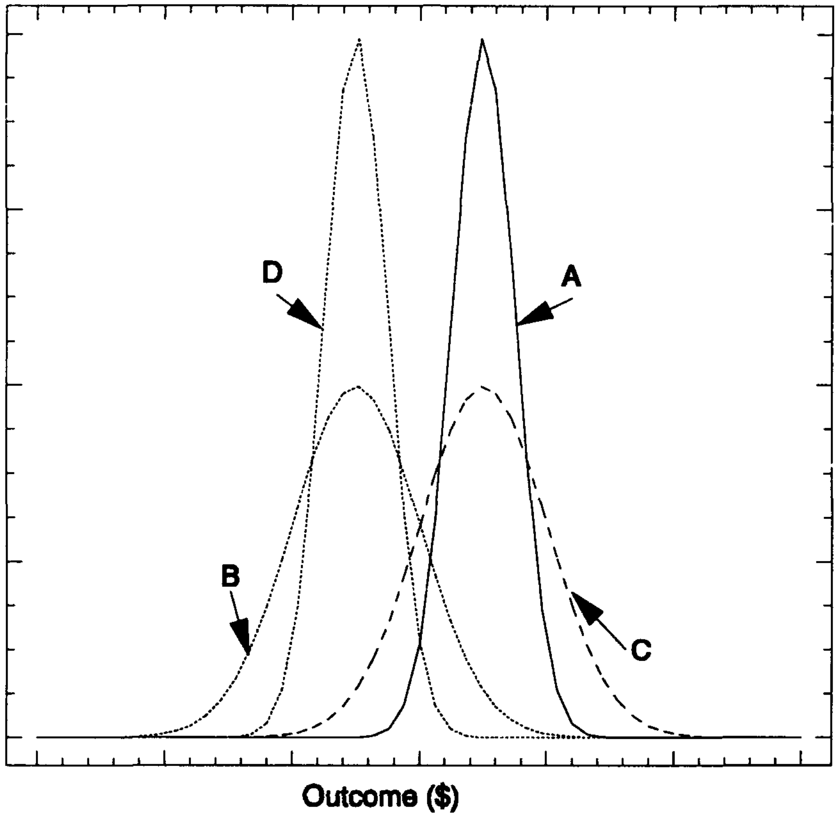

Figure F-6: PDFs for Alternatives A, B, C, and D

This rule holds for all who prefer more wealth to less wealth and is not sensitive to risk preferences.

Figures F-9 and F-10 show the distributions for alternatives A and C. They both have the same expected value for net benefits, but alternative C is riskier. The stochastic dominance rule is based on cumulative distributions. Alternative A initially dominates C, but is eventually overtaken by C. The second stochastic dominance rule is:

> If the cumulative distributions of A and C intercept one or a greater number of times, A is preferred to C if:

$$\int_{-\infty}^{x} (C(X)-A(X))dx,\ x \geq 0 \text{ for all } x \text{ with inequality for some } x,$$

where C(X) and A(X) are the cumulative distributions for alternatives C and A.

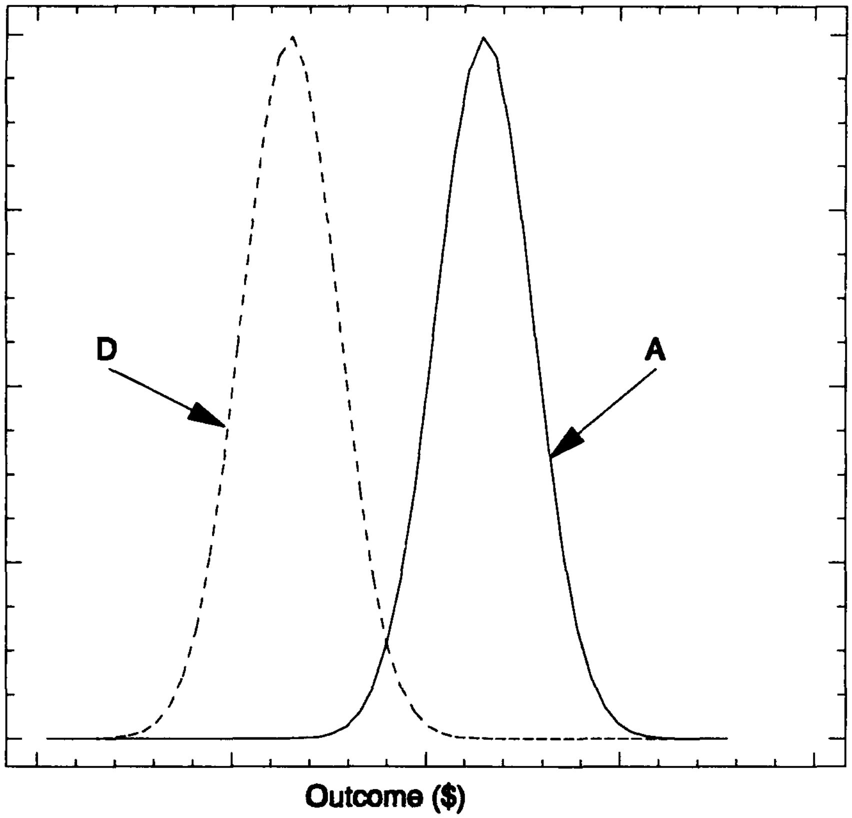

Figure F-7: Stochastic Dominance - PDFs for Alternatives A and D

Although the application of this rule is complex, intuitively it means A is preferred if the area under A(X) is less than the area under C(X).[19]

[19] For a fuller treatment of this subject see Bawa (1982).

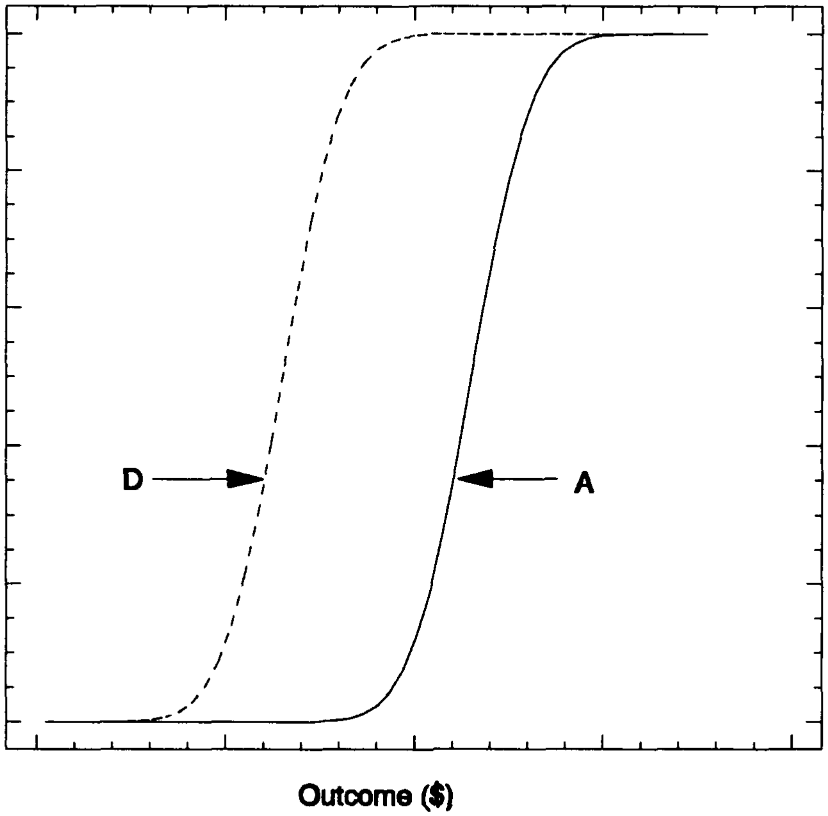

Figure F-8: Stochastic Dominance - CDFs for Alternatives A and D

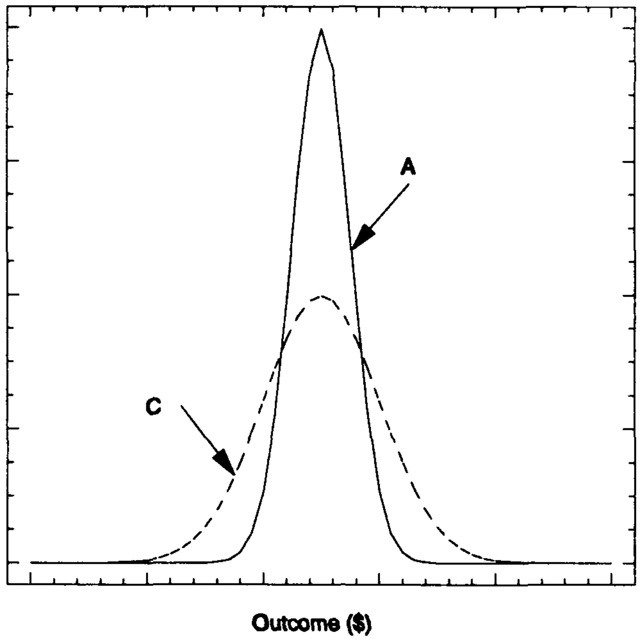

Figure F-9: Stochastic Dominance - PDFs for Alternatives A and C

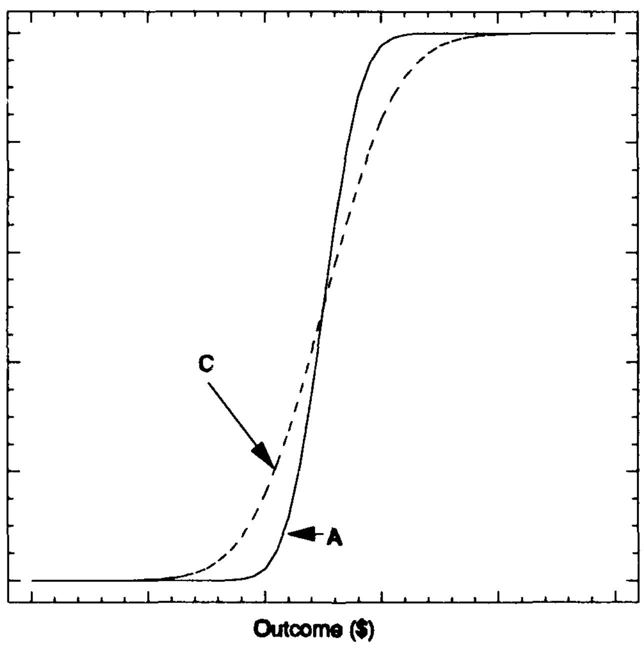

Figure F-10: Stochastic Dominance - CDFs for Alternatives A and C

APPENDIX G

FORECASTING

INTRODUCTION

Forecasting involves predicting future events. An accurate forecast is very important for effective decision making. Many important elements of the planning process, project costs and benefits for example, may depend on these estimates.[1]

Forecasting methods can be qualitative or quantitative. Qualitative methods rely on subjective or judgmental factors. These methods generally use the experience, knowledge, opinions, and judgments of experts to make forecasts. These methods are especially useful when hard facts and historical data are lacking. They are of limited use in complex situations.

Quantitative methods include time series methods and causal methods. Time series methods are statistical smoothing techniques that attempt to forecast future events based on historical data for the event forecast. With these methods past is prologue to future. These methods forecast a variable against time only. Causal methods forecast future time series values by analyzing historic data for one or more variables related to the time series being forecast. The literature on forecasting techniques is voluminous and the discussion that follows is nothing more than an introduction.

COMPONENTS OF A TIME SERIES

Data collected for a specific variable at successive points (annually, monthly, daily, etc.) during a time period constitute a time series. Time series generally exhibit one or more of the following components:

1) trend,
2) cycles,
3) seasonal patterns, and
4) random movements.

A trend is a long term movement of a time series. Cycles are regular movements above and/or below the trend line. The long term trend in waterborne commerce is increasing, but business cycles are well known phenomena that affect waterborne commerce. Trends and cycles both tend to be longer term movements. Cycles may take a number of years to complete. Trends are not apparent until years have passed.

[1] For example, in navigation studies forecasts of future commodity movements and fleet composition dictate project dimensions and therefore costs as well as project benefits.

A seasonal pattern is similar to a cycle except that the seasonal pattern occurs repetitively within 1-year periods. Inland waterways that primarily move a few major commodities exhibit seasonal patterns. Grain movements on the Upper Mississippi peak at the same time each year. Traffic comes to a virtual halt during the coldest winter months when the waterway is iced over.

Random movements do not follow any discernible pattern. Random movements are the variations that are left after we have analyzed the trend, cycles, and seasonal patterns. Because random movements are unpredictable variations in a time series, series with a lot of random variation are very difficult to forecast accurately.

TIME SERIES METHODS

Moving Averages

Moving averages compute an average of the variable for a specific number of the most recent periods and then uses this average to forecast the value of the variable for the next period.

(1) Moving Average = Σ (most recent **n** values of time series)/**n**

To compute a moving average the number of period must be chosen. Three, five and seven periods are common choices. Consider a lock with a moving average for commerce, the last five years measured in thousands of tons as follows:

$$(1{,}850 + 1{,}920 + 1{,}800 + 1{,}875 + 1{,}960)/5 = 1{,}881$$

To get a forecast for the next year we assume the 5-year average of 1,881 will be obtained. Table G-1 presents hypothetical data and compares forecasts of lock traffic using 3-year and 5- year moving averages.

Although the 3-year average is consistently a better forecast in this example, that need not be so. In a relatively stable time series, a longer period may be more accurate. In a series where change is taking place, a shorter period may be more accurate.

The moving average is cheap and easy to use.

Weighted Moving Averages

Moving averages do not give greater weight to events in more recent years. In a dynamic situation, we might want a simple forecast that compromises on stability and sensitivity to recent events and variations. Weighted moving averages are a modified version of the previous measure that assigns greater weight to the more recent data points.

Assignment of weights is purely arbitrary. They can take on any value. If individual weights lie between 0 and 1 and sum to 1, the denominator does not change. If the weights are based on another metric the formula, equation (1) is modified so that the denominator is equal to the sum of the weights.

Table G-1: Moving Average Forecast of Shipping Tonnages

	Actual Tonnage	3-Year Moving Average	3-Year Error*	5-Year Moving Average	5-Year Error*
1970	1,850				
1971	1,920				
1972	1,800				
1973	1,875	1,857	18		
1974	1,960	1,865	95		
1975	2,040	1,978	162	1,881	159
1976	1,980	1,958	22	1,919	61
1977	2,100	1,993	107	1,931	169
1978	2,070	2,040	30	1,991	79
1979	2,150	2,050	100	2,030	120
1980	2,210	2,107	103	2,066	142
1981	2,180	2,143	37	2,102	78
1982		2,180		2,142	

*Actual tonnage - moving average forecast tonnage

With a 3-year weighted average based on the data in Table G-1, assigning a 3 to the most recent year in the average, a 2 to the second most recent and 1 to the oldest, the computation becomes:

$$(3(1800) + 2(1920) + 1(1850))/6 = 1848.$$

This method yields a worse forecast in this instance.

Exponential Smoothing

Forecasts based on exponential smoothing predict time series in the next period based on the moving average of the current period. Like the weighted average it weights recent data more heavily than old data. The basic model follows:

(2) $F_t = \alpha A_{t-1} + (1-\alpha)F_{t-1}$

where

F_t = a forecast of the time series for period t,

A_{t-1} = the actual time series value for period t-1,

F_{t-1} = a forecast of the time series for period t-1, and

α = a smoothing factor whose value lies in the interval [0,1].

The value of the smoothing factor determines the weight of the previous period's actual data. If $\alpha = 1$, we are considering only actual data from the previous period. If $\alpha = 0$ we are basing our forecast entirely on data from the immediately prior period. The following model bases the forecast of the next period 20 percent on the prior period's data and 80 percent on data for periods before that.[2]

(3) $F_t = 0.2A_{t-1} + 0.8F_{t-1}$

Table G-2 presents tonnage forecasts for two simple exponential smoothing models.

Forecast Reliability

No forecast methodology provides a perfect forecast, except on rare occasion or by pure chance. Testing the accuracy of a forecast is important in assessing the quality of a forecast method. In the final analysis it is the result, not the method, that matters. Although there are many and varied measures of reliability, one widely used measure is the mean absolute error (MAE).

MAE is the average of the forecast error. It is the sum of all forecast errors divided by the number of forecasts. To avoid cancellation of errors the absolute error is used. The formula is given by:

(4) $MAE = \Sigma \mid \text{actual - forecast} \mid / \text{number of forecasts}$

The MAE for the 3-year moving average presented in Table G-1 above is 674/9 or 74.89. This means the 3-year moving average was on average off by 75 thousand tons in forecasting traffic. The MAE for the 5-year moving average is 115.4. In general, a smaller MAE indicates a more accurate forecast. The mean absolute percentage error or MAPE is the average of each error expressed as a percentage.

For the two exponential smoothing models presented in Table G-2 it is not clear which model is better by a visual inspection of the results. The MAEs for the models with $\alpha = 0.2$ and 0.4, respectively, are 115.6 and 83.1, indicating the model with $\alpha = 0.4$ yields the more accurate forecast on average.

[2] F_{t-1} is nothing but a forecast value or weighted average based on data from previous periods. Thus, the weight $(1-\alpha)$ assigned to this value is the weight given to past data.

Table G-2: Exponential Smoothing of Forecast Shipping Tonnage

	Actual Tonnage	Alpha = 0.2	Error*	Alpha = 0.4	Error*
1970	1,850				
1971	1,920	1,850	70	1,850	70
1972	1,800	1,864	64	1,878	78
1973	1,875	1,851	24	1,847	28
1974	1,960	1,856	104	1,858	102
1975	2,040	1,877	163	1,899	141
1976	1,980	1,910	70	1,955	25
1977	2,100	1,924	176	1,965	25
1978	2,070	1,959	111	2,019	135
1979	2,150	1,981	169	2,039	51
1980	2,210	2,015	195	2,083	111
1981	2,180	2,054	126	2,134	127
1982		2,079		2,152	46

*Actual tonnage - forecast tonnage

TREND PROJECTIONS

Trend projections are especially useful for medium to long-term forecasts. The method is based on the determination of a trend line based on historical data. Numerous trend line projection methods are available. The most popular trend line projection models are the linear, quadratic, exponential, and spline curves respectively given by:

(5) $Y = a + bT$

(6) $Y = a + bT + cT^2$

(7) $Y = e^{(a + bT)}$

(8) $Y = e^{(a + (b/T))}$

where Y is the forecast value; a, b, and c are parameters of the models; and T is time.

Table G-3: Trend Line Projection Models

	MAE	M[illegible]
Linear $Y = 1763.7 + 40.9 \cdot T$	47.4	2.4
Quadratic $Y = 1847.4 - 1.0 \cdot T + 3.8 \cdot T^2$	41.3	2.0
Exponential $Y = e^{(7.4 + 0.2 \cdot T)}$	45.5	2.3
Spline Curve $Y = e^{(7.6 - 0.2/T)}$	82.6	4.2

Using the tonnage data from Table G-1, the trend line projection models have been estimated. Table G-3 presents the models along with their mean absolute error and the mean absolute percentage error.

CAUSAL FORECASTING METHODS

Methods that focus on the variables that affect or cause trends, cycles, fluctuations, and other variations are causal forecasting methods. The most common causal method, regression analysis, is a statistical technique that uses one or more variables to explain the dependent variable. It is generally far more powerful and accurate than time series methods.

Regression analysis has been covered extensively elsewhere in the literature. Two exceptional texts on the subject that are accessible to anyone with a basic statistical background are Econometrics by Ronald and Thomas Wonnacott (1978) and Theory of Econometrics by A. Koutsoyiannis (1985).

Two regression models are worthy of mention so interested readers can pursue them further. Although they are demanding in use and well beyond the scope of this manual they are particularly useful in forecasting. First, the Box-Jenkins method is particularly useful for forecasting. Its two basic components, the autoregression and the moving average, make it particularly useful in discerning patterns in complex functions where no pattern is readily apparent.

Second, the Box-Cox data transformation method is often useful in determining trends and forecasting. The Box-Cox procedure amounts to dividing the dependent variable by its geometric mean and choosing the best estimator from the linear and log form of the model. Independent variables can also be transformed in this model.

QUALITATIVE FORECASTING METHODS

Many times the historical data are not available for the phenomena we want to forecast.[3] Data may not exist, or it may be too expensive to collect, or it may be readily available but the system that generated the data has changed so drastically that the data are no longer valid.[4]

The quantitative techniques described above and others like them are generally intended for individual decision making. Typically an analyst with the requisite technical skills decides when a model is "good enough." These models are rarely useful for long range forecasts. They are particularly limited in forecasting situations that result from fundamental changes in the structure of the system that produced them. Qualitative forecasting techniques can be useful in bridging some of the gaps that exist with the quantitative tools.

Delphi Method

The Delphi method was developed by the Rand Corporation in the early 1950s. It uses group consensus to make long range or controversial forecasts. There are many variations of the technique but most of them contain the following steps:[5]

<u>Step 1</u>: A panel of experts on the particular problem or topic is formed from both inside and outside the organization. These experts do not usually interact on a face-to-face basis.
<u>Step 2</u>: Each expert is asked to make a prediction on a particular subject on an anonymous basis.
<u>Step 3</u>: Each member then receives a composite feedback of the entire panel's answer to the question.
<u>Step 4</u>: New estimates or predictions are made on the basis of the feedback. The process is repeated as often as desired.

Nominal Group

Closely related to the delphi method is the nominal group technique. Members of a nominal group usually know one another and interact on a face-to-face basis. The opportunity for direct communication among participants is thought by some to lead to better results than the delphi method produces. The basic steps in a nominal group method are as follows:

<u>Step 1</u>: A group of experts is formed.
<u>Step 2</u>: The group generates ideas on the problem or topic in writing.

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[3] Information on dam failures may be unavailable because failures of the type we are interested in may not have occurred.

[4] Data describing the development of the flood plain before the implementation of flood plain development restrictions are not likely to be useful in forecasting future flood plain development after restrictions are enacted.

[5] These steps are taken from Sang Lee's work (1972).

Step 3: Round-robin feedback comes from the group members. Each idea thus generated is written down.
Step 4: Each idea is discussed for evaluation, clarification, or modification.
Step 5: Individual members vote on the recorded ideas for priority, and the group decision is accommodated mathematically, based on rank order or other rating systems.

These methods and hybrids of each have been used extensively within the Federal government and the Corps of Engineers, though less often for forecasts than for dealing with other risk and uncertainty issues. A version of the nominal group technique has been used by some Corps Districts to estimate the annual probability of failure of key components of locks and dams.

Any number of techniques have used expert groups to generate long range forecasts. Futurology is one area in which considerable effort has been made to forecast the future of society based on different sets of assumptions. Scenario writing, brain-storming, artificial intelligence, and other techniques have been used for qualitative forecasts.

Qualitative forecasts are often used when no other method is feasible. Such forecasts can be a useful source of information in situations where the quantitative data for estimating objective probabilities are not as complete as one might like.

FURTHER READING

There are any number of texts on the general and specific topics of forecasting. The Institute for Water Resources' Handbook of Forecasting Techniques (IWR Contract Report 75-7) is a good starting point for exposure to the methods and literature. The Supplement to the report lists 73 techniques for forecasting and describes 31 of the techniques.

Some excellent microcomputer software has been developed for use in forecasting. One of the most accessible is STATGRAPHICS from PLUS*WARE Products. Others include StatPac Gold with the Forecasting Option from Walonick Associates and MINITAB from Statistical Software.

APPENDIX H

SIMULATION

INTRODUCTION

Simulation is a numerical technique of experimentation to determine the dynamic behavior of a system under various conditions.[1] Unlike an analytical model that attempts to represent reality, simulation simply imitates it. The process of simulation involves "running" or "operating" a model to obtain information about how the modeled system operates.

Rather than yielding an optimum solution through algorithms, simulation yields information through experimentation that describes the system. The description of the system can be useful for predicting behavior or performance of the system under diverse conditions.

Figure H-1 presents a simple representation of the simulation process. The analysts must generate input data to feed the model. The model should be designed to provide the output that can be used to measure or evaluate the performance of the objective criteria of the system.

WHEN TO SIMULATE

A reasonable operational rule of thumb is to remember the old adage, "When all else fails, simulate". Although simple simulations can be done by hand, today simulation is almost synonymous with computers because of the advantages in speed of computation, number of iterations, and the decreasing costs of micro-computing.

Simulation is a useful tool in situations of risk or uncertainty. In general, it is best not to use simulation if other analytical techniques can solve the problem. An analytically optimum solution is normally preferred over the type of solution found through the use of simulation. With this in mind, we can look at the advantages and disadvantages of simulation.

ADVANTAGES OF SIMULATION

First, simulation provides a means of studying real world systems or situations without actually changing them. In many situations, it is impossible to perform real experiments. Or, an experiment may involve a high level of risk.[2] Simulating such real-world systems allows decision makers to observe the potential outcome of myriad changes without altering the real system. Simulation is particularly valuable for analyzing complex systems that defy analysis by other techniques.

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[1] This definition and much of the content of this appendix are from Sang M. Lee's Introduction to Management Science (1988).

[2] For example, studying potential dam failures by testing discharges beyond the spillway design is not a feasible means of learning about dam failures.

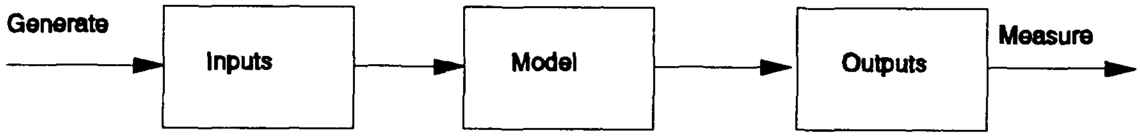

Figure H-1: The Simulation Process

Second, simulation requires a thorough analysis of the problem in order to generate the required data. This analysis can reveal hidden interrelationships or previously unrecognized defects in the system.

Third, there are many options for determining the complexity and cost of the model because simulations are best built step-by-step. The ultimate simulation model is an aggregation of many smaller models representing interrelationships among system variables and components.

Simulations can be an effective training tool for managers and employees alike. The use of ship simulators to train pilots and simulate channel modifications are well known to the Corps' navigation planners. Recent advances in the use of computer animation in micro-computer simulations adds an effective visual dimension to understanding complex systems.[3]

Simulation does not provide prescriptive results. But the descriptive results do more than provide an opportunity for plenty of "what if" sensitivity analysis questions, they require it. The results generated from such analyses provide useful information about the full range of possible outcomes for a particular decision option.

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[3] Dr. Michael Beasley, formerly of Memphis State, created a demonstration simulation with animation that shows the effect of stalls (unscheduled loss of the use of a lock) on inland waterway traffic on the Tennessee River. The animation shows how stalls affect queue lengths, delay times, etc. The animation is particularly useful in showing how the bottleneck can last well beyond the reopening of the lock and how delays at one lock affect traffic at adjacent locks.

DISADVANTAGES OF SIMULATION

First, simulations of complex systems can be time consuming and costly. Developing a reliable model requires considerable data collection effort. Data must be accurate and relationships precise, or additional uncertainty is introduced into the model. Programming a simulation model requires special expertise and it can often be a tedious process.

Second, model results are extremely sensitive to the model formulation. A different specification of a single relationship within the model can lead to very different results. A model built on inaccurate relationships can produce misleading results.

Third, while descriptive results can provide some advantages, their disadvantage is that they do not identify an optimum solution. Simulations generally cannot guarantee an optimum solution or even a very good solution.

Once learned, simulation is a useful and even an exciting tool. The danger inherent in this is that analysts and decision makers may begin to rely on simulations when better techniques and solutions exist.

CHARACTERISTICS OF SIMULATION MODELS

Static versus Dynamic. While most simulations model systems that change over time or interact in a dynamic fashion, simulations can also be static in nature. Location analysis, space allocations, and some financial analyses are examples of static simulation models.

Deterministic versus Stochastic. Any system that varies in a random fashion, and virtually all do, is best modeled as a stochastic simulation. If the expected value of a random variable is known, a stochastic system may be modeled as a deterministic simulation model.[4]

Aggregation and Detail. Degree of aggregation and level of detail are perhaps the most important characterizations of a simulation model. They determine the quality of results and the time and cost requirements of the model. The intended use of the simulation is the best guide in determining the level of detail and extent of aggregation in a world constrained by scarcities of expertise, time, and money.[5]

Time period. Most dynamic simulations describe a system over a period of time. Variables involved in a simulation often change over time. In a detailed simulation, analysts may be interested in knowing the value of important variables at different points in time. Determining a relevant time period is a critical determination. Models concerned with changes that take place

[4] Once we "fix" the value of a random variable we are "acting as if" the value was certain.

[5] A simulation of potential vessel collisions within a channel may be highly aggregated yielding only a description of the number of incidents over a period of time. Alternately, a more detailed simulation may also yield information on systems that contribute to the occurrence of collisions such as the likelihood of fog, strong winds, cross currents, the number of passing situations, combined beam widths in passing situations, etc.

over years should not be based on hour time frames. Likewise, a simulation conducted for weekly analysis should not be based on annual data.

THE SIMULATION PROCESS

Sang Lee (1988) has suggested that simulation is carried out in a series of several steps. Although the steps are not necessarily distinct and sequential, they do describe the basic process of constructing a simulation model.

Step 1: Problem Formulation. The initial step is to identify and formulate the problem or purpose of the simulation. Objectives or performance criteria, variables, decision rules, and parameters must be clearly defined. If the objectives of the simulation are not clearly understood and formulated, the model is not likely to be well constructed. Furthermore, the results will not necessarily lead to a lessening of uncertainty.

Step 2: Analysis of Model Requirements. Data requirements for all relevant variables and parameters must be identified. It is important to determine which variables and parameters are needed to measure system performance as identified in Step 1. Variables should be of two basic types: controllable (policy) and uncontrollable (exogenous).

Step 3: Model Development. It is generally best to build the ultimate simulation model from a number of related smaller models. It is essential that the smaller models be well formulated and operating properly before the interrelationship of these models is established. Flowcharts are useful tools in identifying the logical linkages among the smaller models.

Step 4: Programming the Model. The verbal/mathematical description of the model must be transformed by a computer language into a model that can be analyzed on the computer. This programming and de-bugging step is often the most time-consuming and difficult.

Step 5: Validation of the Simulation Model. Test runs are required to validate the model. Typically, a simulation of actual past conditions is run and the results of the simulation are compared to the actual results. If the results of the test run are reasonably close to the observed results for several test runs, the model is validated. If the test results deviate from actual outcomes the simulation model must be revised.

Step 6: Perform Simulation. Once the model is validated it must be run. Simulation results under various experimental designs are typically obtained. It is vitally important to have the decision maker participate in the analysis at this point. Because the results are descriptive of the system specific certain conditions, obtaining practical and useful results require the decision makers input. The simulation must be describing a realistic and relevant system and situation to have value in reducing uncertainty.

Step 7: Analysis of Results. Simulation usually yields operating statistics in the form of descriptive statistics and probability distributions. Successful interpretation of these results is essential to the usefulness of the simulation.

MONTE CARLO PROCESS

The Monte Carlo process is often confused with the simulation process. It is not a simulation model or a simulation process. The Monte Carlo process is a procedure that generates values of a random variable that may be of interest in a simulation process. It is an important technique used in stochastic simulation. Because it is so closely identified with simulation models it will be briefly described here.

The Monte Carlo process is a two-stage procedure.[6] In stage one, a random number generator produces a number. These numbers have a uniform probability distribution, i.e., each number has an equal probability of being chosen. In stage two, the random number is transformed into a specific value of the random variable of interest. This random variable has a specified distribution.

Uniformly distributed random numbers can be generated in a number of ways. For simple problems, they can be generated by a table of random numbers, rolling dice, flipping coins, spinning a number wheel, ping-pong balls in an air chamber, or any of a number of methods.

A table of random numbers is a long sequence of numbers generated by a numerical technique that results in a repeating sequence of numbers after a number of iterations. These are not true random numbers but pseudo-random numbers. To use a table of random numbers one can select a number in a random fashion, or numbers can be selected according to a fixed pattern, e.g., every fifth number from the top.[7]

A popular method for generating pseudo-random numbers is the Mid-Square Method. Using a starting number, or seed, the seed is squared and the middle digits are used as a random number. This random number becomes the seed for the next random number, i.e., it is in turn squared and the middle digits selected. Table H-1 provides an example of this method. Random numbers are designated by r_i. The middle four digits have been chosen in the example, but it could have just as easily been the middle two or any other number of digits depending on the size of the seed and the analyst's need.

Random numbers can be generated easily with computers. Many micro-computer software packages have routines for generating random variables. Several of the most popular programming languages, e.g., Basic and FORTRAN, have the capability of generating random numbers with a simple program.

The second step of the Monte Carlo process is transforming the random number into a value for the random variable of interest. Transformations can be based on a tabular form, a graphical

[6] Generally attributed to the work of John von Neumann during development of the atom bomb during World War II.

[7] For example, to obtain a starting point close your eyes and drop a pencil on the page or open a book at random and use the page number as the first number taken. Numbers are taken in sequence after the staring number is chosen.

Table H-1: An Example of the Mid-Square Method of Random Number Generation

Seed		=	4,745			
	$(4,745)^2$	=	22515025;	r_1	=	5,150
	$(5,150)^2$	=	26522500;	r_2	=	5,225
	$(5,225)^2$	=	27300625	r_3	=	3,006

method, or a mathematical transformation technique.

The tabular method is simplest when it can be used. It is based on the cumulative distribution function of the random variable of interest. Table H-2 provides an example of this method for a very simple case. In this example, probabilities P(O) are known for the disjoint outcomes O that a ship will pass another ship in a channel, in a bend, or not at all. (The outcomes are called disjoint outcomes because a single ship passing can only be of one type or another.) The cumulative probability is given by F(O). In this case, it is assumed that the random numbers are defined over the interval 0-99. Thus, using the two right digits in the random numbers generated in Table H-1 the values are 50, 25, and 06. The first value indicates no pass, the next two indicate passes in the channel.

Figure H-2 presents the same transformation in graphical form. In the figure, the random number can be found on the relative cumulative probability axis, which is a simple transformation of the cumulative probability. The corresponding value of the random variable can be read from the horizontal axis.

SIMULATION LANGUAGES

Most simulation programs share common functions, such as generating random numbers, advancing time, and recording intermediate results for analysis. The best-known simulation languages are described below.

GPSS. Developed by IBM in the early 1960s, the latest version is GPSS/H from Wolverine Software. GPSS/PC is the micro-computer version. Effective for systems with complex processes, GPSS is also compatible with queuing and network problems. Knowledge of computer programming is not a prerequisite for using GPSS.

SIMSCRIPT. Developed by the RAND Corporation in the early 1960s, it is a high level language for discrete event simulation. Its latest version, SIMSCRIPT II.5, was updated by CACI in 1983. SIMSCRIPT PC is the micro-computer version. This is one of the most popular simulation languages available today.

Table H-2: Transformation of Random Numbers to Random Variable Values

Outcome(O)	Value(O)	P(O)	F(O)	Random Number Interval
Pass in bend	0	0.05	0.05	0-4
Pass in channel	1	0.35	0.40	5-39
No pass	2	0.60	1.00	40-99

SIMULA. Developed by O. J. Dahl and K. Nygaard and released by the Norwegian Computing Center in 1965, SIMULA is very similar to SIMSCRIPT. The latest version is SIMULA 67.

SLAM II. Developed by Alan P. Pritsker in 1979, SLAM II is a FORTRAN-based simulation language. Effective use of the advanced features of this language requires knowledge of FORTRAN.

DYNAMO. Developed by P. Fox and A. Pugh of M.I.T. in 1959, this language is particularly well-suited to large-scale industrial systems. Micro-DYNAMO is the micro-computer version. DYNAMO requires very little computer programming knowledge.

In addition, there are many special-purpose simulation languages for micro-computers on the market. They include ASSE, DYNSIM, GASS, HYSIM, MAXSIM, Micro-NET, SIMAN, and TUTSIM. Stochastic simulation programs particularly well-suited to network problems include GEMS-II, Q-GERT, VERT III, and NETWORK II.5.

@RISK, a Lotus 1-2-3 add-in developed by Palisade Corporation is a simple to use and surprisingly powerful simulation tool. One of its major advantages is that it can be used in any problem setting that can be modeled by a spreadsheet. PRISM, a programming language developed by Palisade, is another accessible and easy to use simulation tool. @RISK and PRISM were used extensively to conduct the risk and uncertainty analysis developed in the case studies that accompany this manual and appendices.

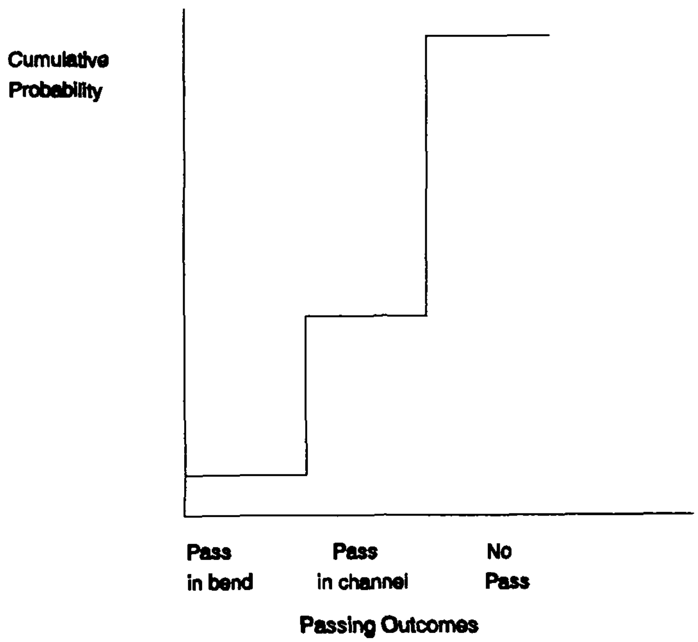

Figure H-2: Graphical Transformation of Random Numbers to Random Values

APPENDIX I

DECISION MAKING UNDER UNCERTAINTY

INTRODUCTION

We often face uncertainty when completely new situations are confronted. We may be uncertain about outcomes, results, or probabilities of outcomes. A number of decision making criteria have been developed to generate information for decision making in an uncertain environment. Most decision making under uncertainty involves:

1) Alternative courses of action.
2) Possible events (outcomes, or states of nature).
3) Conditional payoffs (results) for the action/event Combination.
4) Unknown probabilities of the events.

Several decision making criteria utilizing maximum expected values will be considered based on the following hypothetical situation. Consider a town with a flood problem that has three alternative future levels of development, with or without a project. Dense development means more runoff and greater damages, moderate development is the expected level of development, and minimum development would mean no worsening of the flood problem and less damage. Three alternative projects are being considered: a series of small detention reservoirs, a channel improvement and a levee system. Table I-1 presents net benefits based on reduced expected annual damages of the three alternatives under the possible development schemes.

PARTIAL PROBABILITIES

Suppose the best available judgment indicates a 40 percent chance of moderate development but gives no idea how the remaining 60 percent is divided between the dense and minimal development states. We can at least estimate the indifference probabilities for the three alternative projects; that is, the probabilities for each possible state at which the expected value of the benefits of each alternative project are the same.

Table I-1 tells us the detention reservoir alternative yields net benefits of $100,000 with certainty. Thus we seek the probability of dense and minimal development that leaves us indifferent between the channel and levee alternatives. Letting **p** be the probability of dense development, (0.6 - **p**) is the probability of minimum development.

Table I-1: Conditional Net Benefit Matrix - Payoffs ($)

	Development Scenarios		
Alternative Project	**Dense**	**Moderate**	**Minimal**
Detention Reservoir	$100,000	$100,000	$100,000
Channel Improvement	200,000	160,000	20,000
Levee System	250,000	180,000	(120,000)

The expected value for each project is given by:

(1) E(Channel) = $200,000p + $160,000(0.4) + $20,000(0.6-p)
= $180,000p + $76,000

(2) E(Levee) = $250,000p + $180,000(0.4) - $120,000(0.6-p)
= $370,000p

(3) E(Reservoir) = $100,000

To be indifferent between the channel or levee alternatives and the reservoir project, the expected value of each must be exactly equal (assuming risk neutrality). First, we can look at the channel and reservoir alternatives. We know the probability of moderate development is 0.40. Setting (1) and (3) equal to each other and solving for **p** gives us 0.1333, the probability of dense development at which we are indifferent between the channel and the reservoir projects. Next, solving (2) and (3) we find **p** of 0.2703, the probability of dense development at which we are indifferent between the levee and the reservoir. And solving (1) and (2) gives us **p** of 0.40, where we are indifferent between the channel and the levee alternatives.

Figure I-1 shows the expected value for each alternative at different probabilities of dense development, given our probability of moderate development of 0.40.

This approach identifies some critical probabilities. Given that the probability of moderate development is 0.40, we see that if the probability of dense development is 0.1333 or less the reservoir alternative is best. If the probability of dense development is between 0.1333 and 0.4, the channel project is best. And if the probability of dense development is greater than 0.4, the levee project is best. Professional judgment on the probability of dense development would guide the decision process in this case.

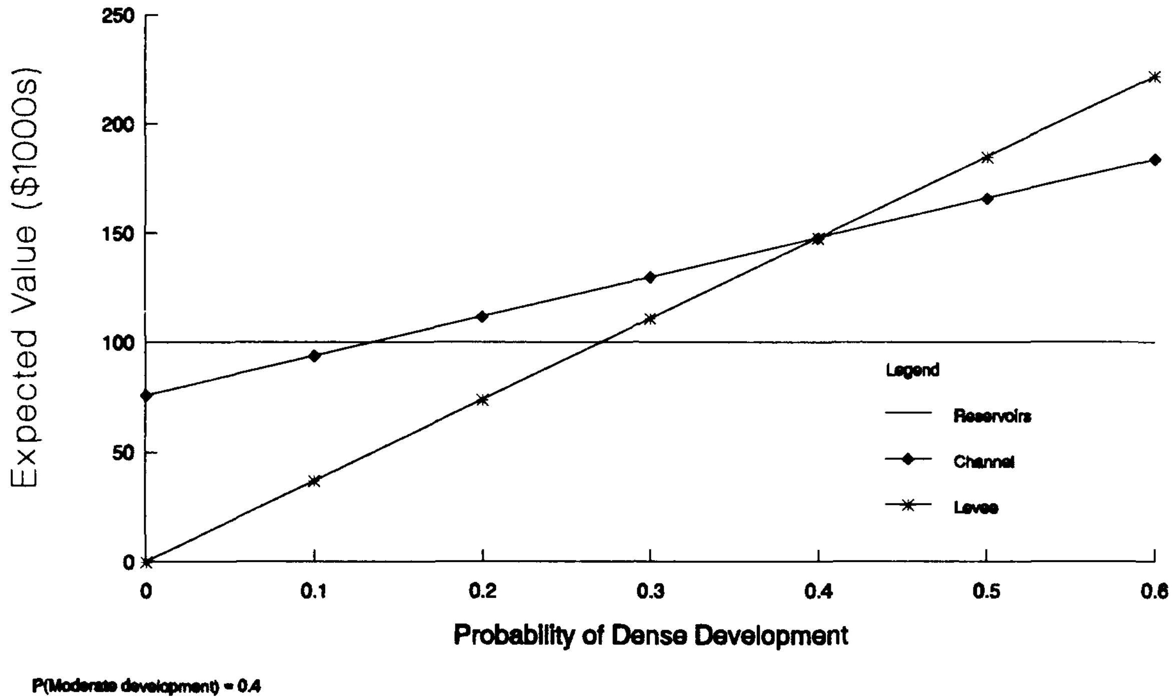

Figure I-1: Expected Values Using Partial Probabilities

LAPLACE CRITERION

In cases where partial probabilities are not known, other techniques must be used. One possibility is to assign equal probabilities to all possible outcomes. Using this criterion with our three expected value equations developed earlier and assuming we don't know the probability of moderate development, the expected values of the net benefits of the three alternatives are:

E(Reservoir) = $100,000
E(Channel) = $127,000
E(Levee) = $103,000

Based on the Laplace criteria of equal probabilities of outcomes, the channel alternative yields the largest expected value and is the best choice.

MAXIMIN CRITERION

Risk averse behavior; i.e., a pessimistic outlook on the future, expects that the worst possible outcome will be realized for each alternative. The alternative that yields the "best" of the worst outcomes, or in this case, maximizes minimum benefits, is chosen.

Under the maximin, or Wald, decision criterion, only the minimum payoffs of each alternative are considered. In our example, the reservoir is chosen because its worst possible outcome of $100,000 exceeds the worst possible outcome of either the channel ($20,000) or the levee (-$120,000) alternatives. This approach relies on partial information and can be an unrealistic way to makc decisions. In the present case, it ignores the fact that under any but the worst case scenario the reservoir is the worst choice.

MAXIMAX CRITERION

The maximax is the exact opposite of the maximin criterion. It is based on an optimistic outlook or risk preferring behavior. This criterion also uses partial information considering only the maximum payoff for each alternative. The alternative that yields the "best" of the best outcomes, or the maximum maximum payoff, is chosen. Under this criterion, the levee is selected because its best possible outcome of net benefits of $250,000 is higher than the best possible outcome of either the reservoir ($100,000) or the channel ($200,000) alternatives.

DOMINANCE CRITERION

The dominance criterion is a pairwise comparison technique that can reduce the number of alternatives considered, but may not yield a unique solution. An alternative is dominated when there is another alternative that yields a larger payoff (expected value) for every possible state of nature (in this example, level of development). If there is only one alternative remaining after applying this criterion it is an optimal alternative. The problem with this criterion is evident in Table I-1 where there is no dominant alternative. The channel dominates the reservoirs for dense and moderate development, but not minimal development. The levee dominates both the channel and reservoirs for dense and moderate development but is dominated by each for minimal development.

HURWICZ CRITERION

Leonid Hurwicz suggested a criterion that is a compromise between the maximin and maximax criteria. He used a coefficient of optimism (α) as a measure of the decision maker's optimism. The coefficient ranges from 0 to 1. An $\alpha = 0$ indicates total pessimism (maximin criterion) and $\alpha = 1$ indicates total optimism (maximax criterion). The coefficient of pessimism is thus defined as $1-\alpha$.

Hurwicz defined the weighted payoff as:

(4) Weighted payoff = α(maximum payoff) + $(1-\alpha)$(minimum payoff)

Using a coefficient of optimism of 0.5, and therefore a coefficient of pessimism of 0.5, the weighted payoffs (WP) of the three alternatives are:

WP (Reservoir) = 0.5(100,000) + 0.5(100,000) = \$100,000
WP (Channel) = 0.5(200,000) + 0.5(20,000) = \$110,000
WP (Levee) = 0.5(250,000) + 0.5(-120,000) = \$65,000

Under this criterion the channel alternative is best.

If the decision maker is unable to determine his or her α it is possible to determine some critical alpha values (for instance, where weighted payoffs of two alternatives are equal) and ask the decision maker if his or her value is greater or less than these values.

MINIMAX CRITERION

The minimax, or regret criterion, is based on the economic concept of opportunity cost. For a given scenario or state of nature, different alternatives may yield different payoffs. The opportunity cost of an alternative for a particular state of nature is the difference between its payoff and the payoff of the highest-yielding alternative for that state of nature. For example, the opportunity cost of the reservoir alternative for our moderate development scenario is \$80,000, as the reservoir's payoff of \$100,000 is less than the highest possible payoff of \$180,000 yielded by the levee.

With the minimax criterion, the decision maker wants to minimize the maximum opportunity cost. To do this, we first find the maximum opportunity cost for each alternative across all possible scenarios. The alternative with the lowest maximum opportunity cost is selected. Table I-2 illustrates the minimax criterion for our example. From this table, the channel project is our selected alternative as it has the lowest maximum opportunity cost of \$80,000.

Table I-2: Use of Minimax Criterion

	Opportunity Cost (OC) for Development Scenarios			
Alternative Project	**Dense**	**Moderate**	**Minimal**	**Max OC**
Detention Reservoir	\$150,000	\$80,000	\$0	\$150,000
Channel Improvement	50,000	20,000	80,000	80,000
Levee System	0	0	220,000	220,000

APPENDIX J

BAYESIAN INFERENCE

INTRODUCTION

Prior beliefs about the value of a parameter may play a key role in its estimation. Bayesian theory is a method for formally taking such information into account. Bayesian statistics provide a way of combining information from a sample and from prior information to produce a new way of estimating probabilities of events. In large samples, the Bayesian estimate is practically the same as the classical statistical estimate based on the sample alone. Thus, the Bayesian technique is used primarily for small samples.

AN EXAMPLE USING BAYES' THEOREM

An introduction to Bayesian analysis is best developed with a hypothetical example. A utility company transportation manager is considering shipping coal by waterway later this month. From National Weather Service data, she learns that 30% of all months on the waterway that she will use have been bad months for shippers, i.e., they meet with adverse weather conditions that can be expected to lead to delays.

To get more information she contacts a friend working with the Atlantis District of the Corps. This friend is an expert analyst who uses data from the Corps' Lock Performance Monitoring System (PMS) to pronounce months at specific locks "good" or "bad" for shippers. Of all the months that have proved to be bad for shippers on this waterway, her friend has correctly predicted 90% of the "bad" months (quotation marks will indicate the friend's opinion; no quotation marks indicate the actual state of the month). In other words her friend is wrong 10% of the time. The friend is almost as accurate predicting "good" months; she has correctly predicted a good month 80% of the time (wrong 20% of the time).

What is the chance that any month will actually be bad for shippers? Our transportation manager can establish a probability based on information under three situations:

1) Before she consults her friend,
2) If the friend predicts a "good" month, and
3) If the friend predicts a "bad" month.

Before consulting the friend, the probability of a bad month is 0.3, the proportion of all months that are bad. This is the only information available. Figure J-1 shows the tree analysis that aids in understanding how the friend affects the probabilities. The first branching shows the 70% of the months that are good and the 30% that are bad. The second branching shows how well the friend predicts the conditions. The top branch shows that of the 70% of all months that are good, the friend correctly predicts 80% of them as "good". Thus, 56% (80% of 70%) of all good months are correctly identified as such. This percentage is marked in the right column, as are the percentages for the other four possibilities.

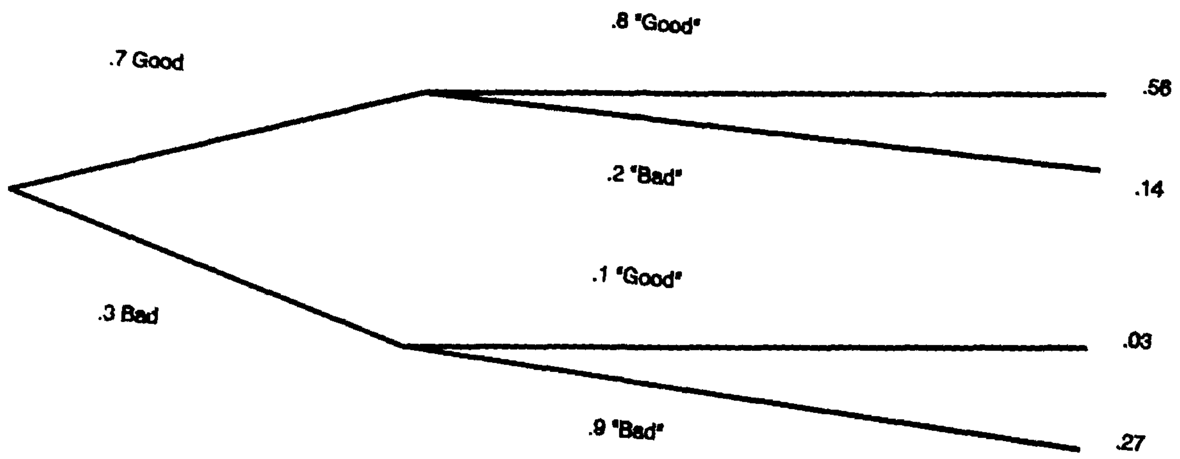

Figure J-1: Bayesian Tree Analysis Example

Altogether 59% (56% + 3%) of all months are judged "good". Only a small proportion of the months the friend predicts are "good" actually turn out to be bad. The conditional probability that a bad month occurs given the friend's prediction of "good" is:[1]

$$(1)\quad p(\text{bad} \mid \text{"good"}) = \frac{p[\text{BAD} \cap \text{"GOOD"}]}{p[\text{"GOOD"}]} = .03/.59 = .05$$

We see that once the month has been pronounced "good" by the friend, the probability of a bad month drops from the original .30 down to .05.

Forty-one percent of all months are judged "bad" by the friend (27% + 14%). Once the friend predicts a "bad" month, the conditional probability of the month being bad is:

[1] See Appendix C for a discussion on conditional probability.

$$(2)\quad p(\text{bad} \mid \text{"bad"}) = \frac{p[\text{BAD} \cap \text{"BAD"}]}{p[\text{"BAD"}]}$$

$$= .27/.41 = .66$$

Thus, once the friend predicts a "bad" month, the probability of a bad month increases from the original .30 to .66.

We can also determine the conditional probabilities of a good month once the friend has made a prediction:

$$(3)\quad p(\text{good} \mid \text{"good"}) = .56/.59 = .95$$

$$(4)\quad p(\text{good} \mid \text{"bad"}) = .14/.41 = .34$$

The introduction of additional information (the friend's analysis) changes the likelihood of a good or bad month occurring compared to our original information (i.e., the 30/70 NWS ratio). The better estimates result because we learn from the additional information offered by our expert.

Figure J-2 presents the information from the above computations in a different (i.e., reverse order) format called a reverse tree. In this figure, the first branching begins with the .59 "good" and .41 "bad" result from Figure J-1. The second branching now shows the actual conditions of the months and the answers the transportation manager is seeking. If the month is judged "good", there is a .95 probability it will actually be a good month and only a .05 probability of a bad month occurring. Similarly, if the month is judged "bad", there is a .66 probability it will be a bad month and a .34 probability the month will be good.

Figure J-3 presents these results in a sample space format. Conceptually, each month is presented as a dot. There are four rectangles in the figure. Cross-hatched areas represent bad months, dotted areas good months. "Bad" months that turn out bad are shown in the cross-hatched area at the top of the figure. "Good" months that turn out to be bad are shown in the dotted rectangle at the top of the figure.

"Bad" months that turn out good are shown in the vertical cross-hatched rectangle in the bottom of the figure. "Good" months that turn out good are shown in the dotted rectangle in the bottom half of the figure.

The top half of the figure comprises 30 percent of the entire figure and consists of the 30 percent of all months that are actually bad. The bottom half comprises the 70 percent of all months that are actually good. Thus, wrong guesses are the dotted rectangle in the top half and the cross-hatched area in the bottom half. Using the areas in the sample space the posterior probabilities of equations (1) through (4) can be obtained. For example, the values used in equation (2) above are shown on the figure.

This technique applies Bayes Theorem. The original probabilities are called the prior probabilities; they appear in the first branching of Figure J-1. The prior probability is the belief

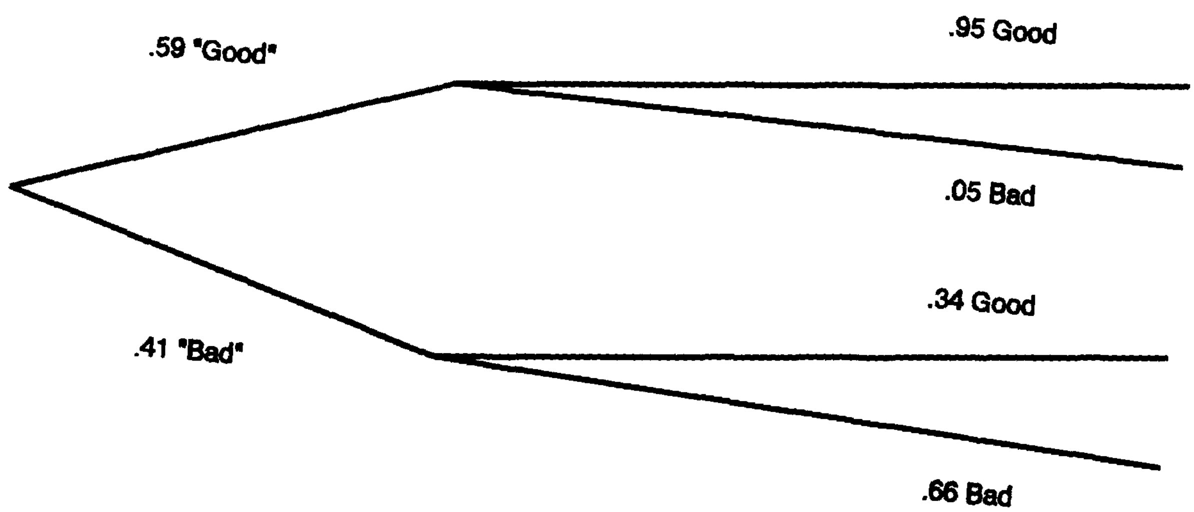

Figure J-2: Bayesian Tree Analysis - Conditional Probabilities

that the bad/good month ratio is 30/70. The test in the example consisted of acquiring additional information from an expert friend. The probabilities after testing are called the posterior probabilities; they are the shown in the last branching of Figure J-2. The posterior probabilities are the relevant probabilities. They take the prior probabilities into account as well as the information provided by testing. The point of Bayes Theorem, shown in Figure J-4 is that prior probabilities combined with information from a test or sample yield posterior probabilities, i.e., probabilities that incorporate prior beliefs and test results.

Figures J-5 and J-6 illustrate how the analysis of Figures J-1 through J-3 can be applied in general. Beginning with Figure J-5, for a state Θ, we have a prior probability $p(\Theta)$, incorporating all our knowledge about Θ (in our example, the probabilities of good and bad months before the friend is consulted). The term $p(X_1|\Theta_1)$ is the likelihood function, representing the probability of the test reflecting the actual state (i.e.,the probability of a "good" or "bad" prediction being correct). Equation (a) of Figure J-5 gives the portion of a state identified by a test (or, the actual percentage of good months predicted as "good"). The posterior probability of Θ_1 given X_1 is a conditional probability defined as:

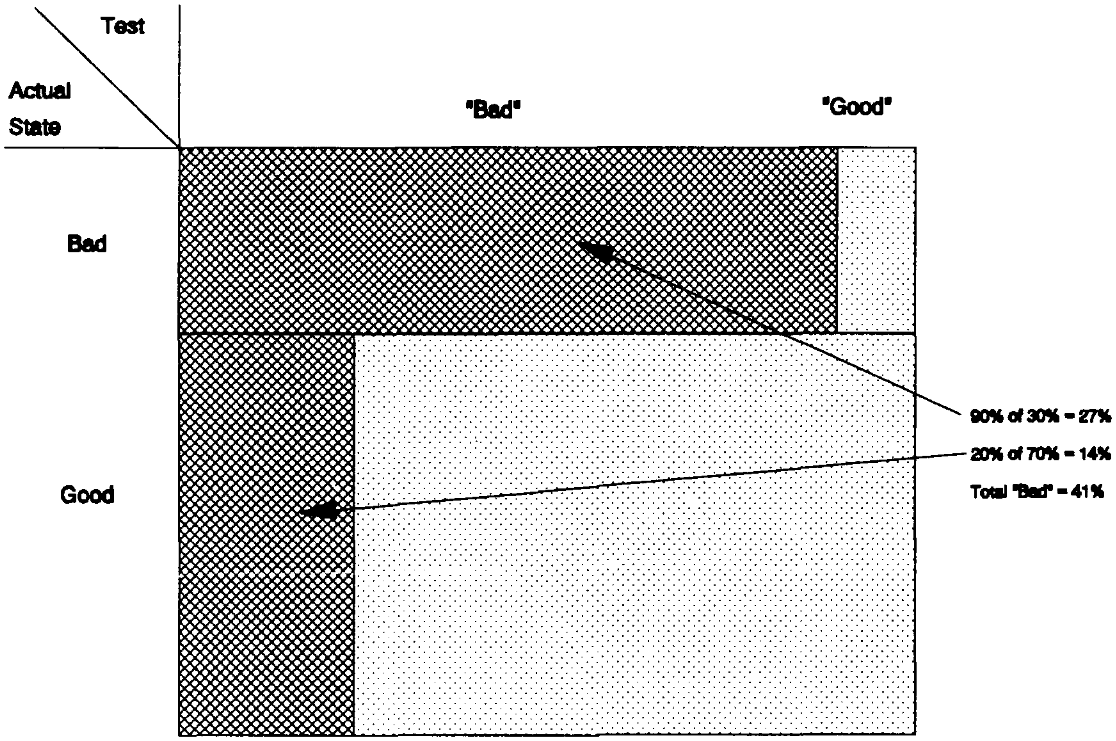

Figure J-3: Bayes' Theorem Sample Space

(5) $p(\Theta_1|X_1) = p(\Theta_1,X_1)/p(X_1)$

or

(6) $p(\Theta_1|X_1) = p(\Theta_1)p(X_1/\Theta_1)/p(X_1)$

Equation (6) can be written in words as:

(7) posterior α prior x likelihood

where α means "is proportional to." This is a straightforward restatement of the results of our example. Intuitively, it says that the posterior probabilities depend on what you believe to be true and what the data tells you. Figure J-6 presents the same information in a reversed logic tree.

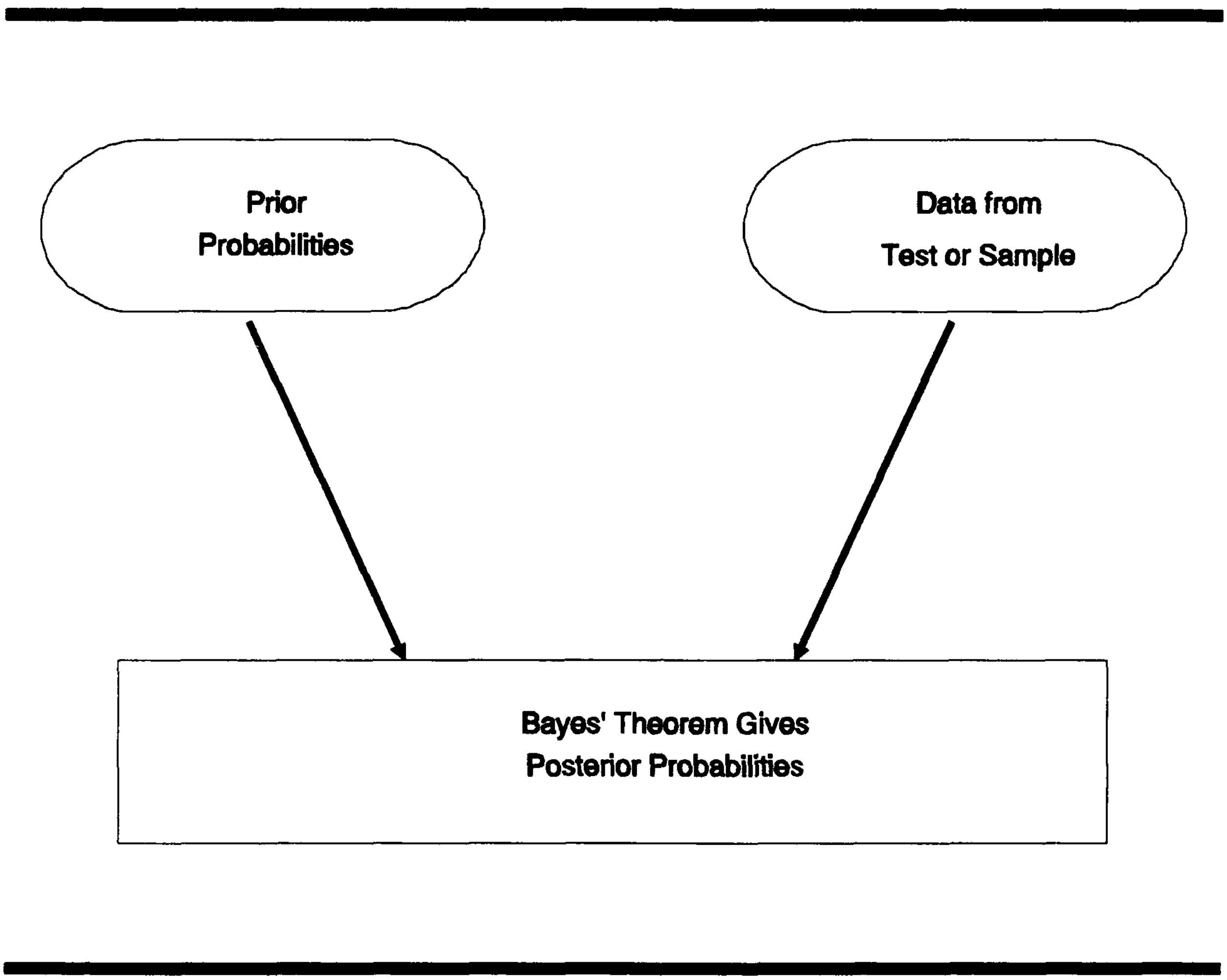

Figure J-4: The Logic of Bayes' Theorem

BAYESIAN INFERENCE

Bayesian inference can be used to calculate posterior distributions of population proportions, means, slopes in regressions, etc. Standard errors, confidence intervals, and Bayesian decision theory are also based on the results presented above. The previous example is expanded and modified to illustrate in more explicit detail the type of analysis that is possible with Bayesian theory. The next example looks at the posterior distribution of the population proportion, π.

The same utility manager is weighing shipping coal later this month by waterway or rail. The waterway is cheaper unless there is a long delay. Examining 200 months of PMS data he has found the proportion of shipments delayed by lock stalls ranges from 0 to 40%. Table J-1 contains a summary of the information. There were no observations of delayed shipment proportions beyond 40% so intermediate levels above 40% and less than 100% are not considered.

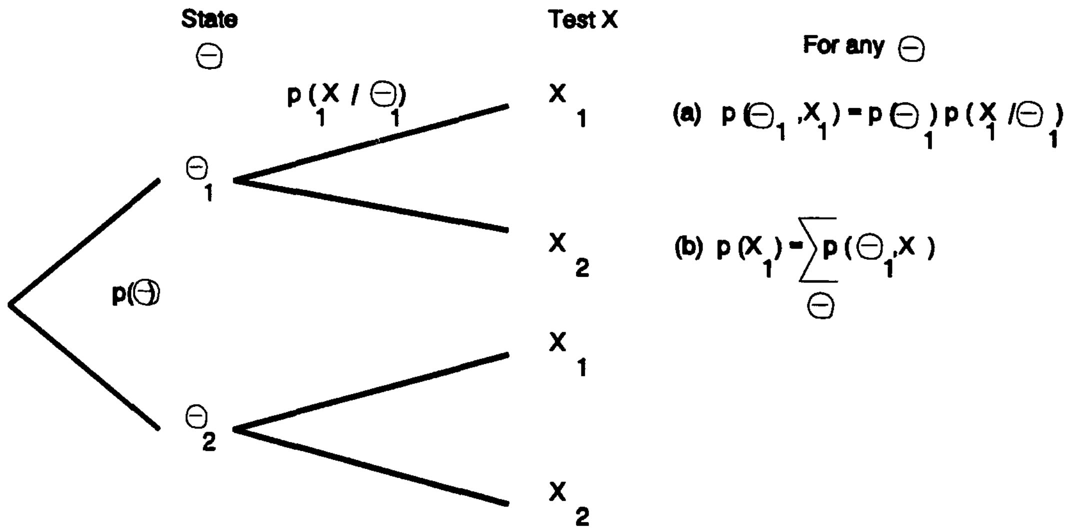

Figure J-5: Bayes' Theorem and Probabilities

The manager regards waterway transportation this month as acceptable only if the proportion of delays is less than 15%. Based on the summary of PMS data in Table J-1 the probability of a $\pi < 15\%$ is .01 + .15 + .2 = .36. Now suppose the manager knows that so far this month 5 shipments have been made. Of these, 3 have met with delays. What is the probability of $\pi <$ 15% this month given this information?

Figure J-7 shows the prior, posterior and likelihood distributions (all values have been rounded). The prior distribution for discrete values is given by plotting columns (1) and (3). To calculate the posterior distribution we need the likelihood function, i.e., the likelihood of getting 3 bad shipments out of 5. This is given by the binomial distribution for a sample size 5 and 3 successes.[2] The values for the likelihood of the given proportions are shown in column (4). Following equation (7), the likelihood function times the prior yields the values in column (5). These values do not sum to 1.0 so they must be divided by the sum of column (5) to yield the

[2] Appendix D presents an example using the binomial distribution.

Table J-1: Calculating the Posterior Distribution of a Population Proportion

Given Prior Distribution for π			Calculations to Obtain Posterior Distribution		
(1)	(2)	(3)	(4)	(5)	(6)
Proportion (Probability) Delays π	Number of Shipments	Relative Number of Shipments	Likelihood of π (Binomial)	Prior Times Likelihood (3) x (4)	Dividing by .047 Yields Posterior
0%	2	.01	0	0	0
5%	30	.15	.001	.000	.004
10%	40	.20	.008	.002	.034
15%	42	.21	.024	.005	.109
20%	34	.17	.051	.009	.185
25%	26	.13	.088	.011	.242
30%	16	.08	.132	.011	.224
35%	8	.04	.181	.007	.154
40%	2	.01	.230	.002	.049
45%	0	0	.276	0	0
.	.	.	.	.	.
.	.	.	.	.	.
70%	0	0	.309	0	0
.	.	.	.	.	.
.	.	.	.	.	.
100%	0	0	0	0	0
	200	1.00		.047	1.00

posterior probabilities.

The prior probability of less than 15% chance of a delayed shipment is .36. The posterior probability is .04. The posterior probability presents more information than the prior probability. The magnitude of difference in the two could conceivably lead to entirely different decisions. Thus, given that 60 percent (3 of 5) of shipments so far this month have been delayed there is less than a 4 percent chance this month will have 15 percent or fewer delayed shipments.

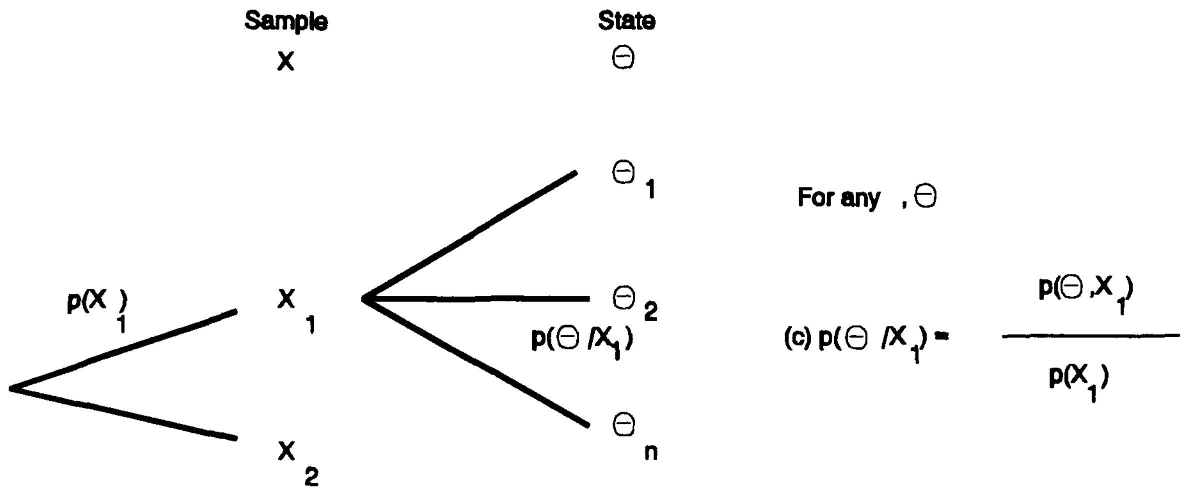

Figure J-6: Bayes' Theorem Reverse Tree

Although a full treatment of Bayesian theory is well beyond the scope of this appendix, the example shows how it can be applied to situations of risk and uncertainty in planning and decision making.[3] Bayesian techniques lend themselves to situations where some, but insufficient, data are available and expert opinion is accessible. It can be used in selecting model parameters and other key variables that may affect the feasibility of a project. Expert opinion is extremely valuable in estimating the probabilities of failure for Corps' projects or their critical components. Sample data on failures may be available in the professional literature or Corps' data bases such as PMS or Rehabilitation, Evaluation, Management and Repair (REMR).[4] A

[3] For an excellent introduction to Bayesian theory, used extensively throughout this appendix, see Wonnacott and Wonnacott's Introductory Statistics (1985).

[4] As these appendices are prepared for press IWR is sponsoring research by Dr. Harry Kelejian, University of Maryland, to estimate the probability of lock-related delays at locks on the inland waterway. Phase I of that research is complete. It is anticipated that subsequent research will show how Bayesian theory, combining professional judgment and empirical evidence, can be applied to the estimation of probabilities of lock "failure."

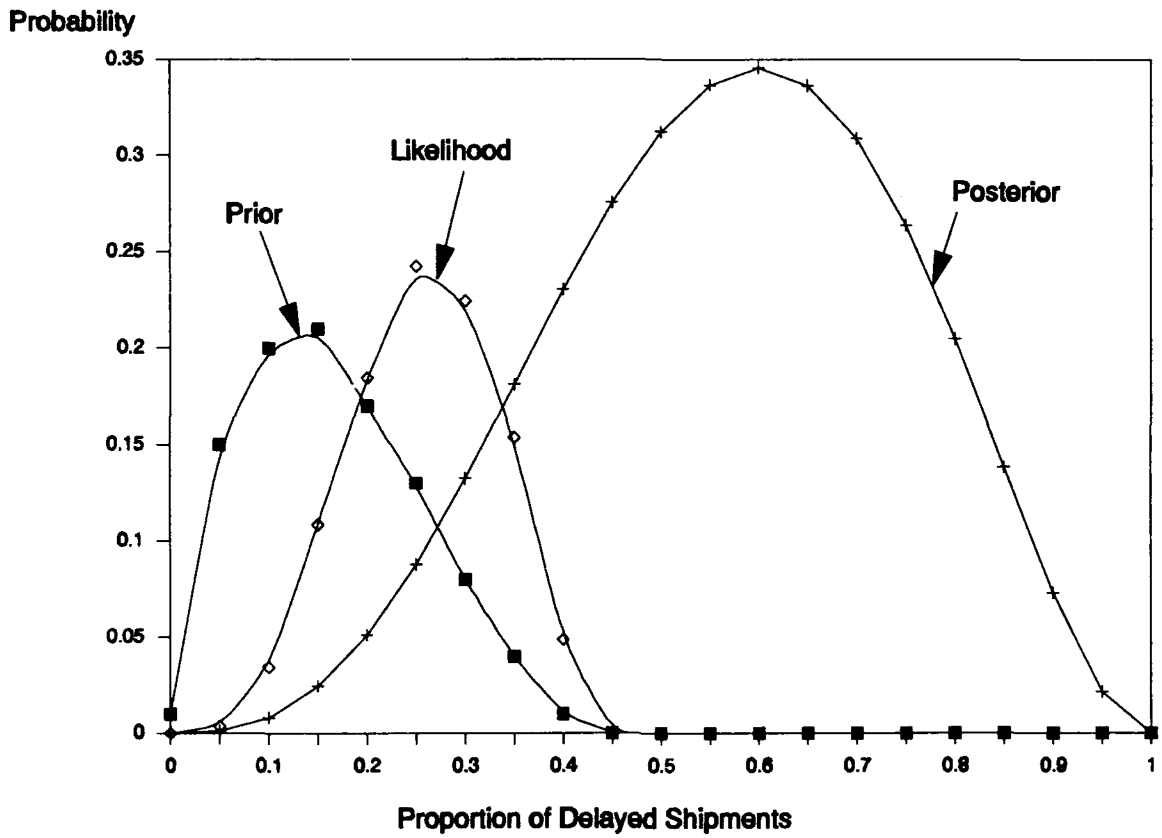

Figure J-7: Prior, Likelihood, and Posterior Distributions

Bayesian approach can be helpful in refining estimates of frequency of many other rare events.

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